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TERRESTRIAL MAGNETISM

THE EARTH'S MAGNETISM

By

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Special Publication No 117

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By Daniel L. Hazard, *Assistant Chief, Division of Terrestrial Magnetism*

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INTRODUCTION

In 1902 this bureau issued a publication entitled "United States Magnetic Declination Tables and Isogonic Charts for 1902, and Principal Facts Relating to the Earth's Magnetism," by L A Bauer, at that time chief of the division of terrestrial magnetism The declination tables and charts have been superseded by later publications, as more accurate and more detailed information regarding the earth's magnetism in the United States has been secured in the progress of the magnetic survey of the country The demand for general information regarding the earth's magnetism has been met by reprints of Principal Facts Relating to the Earth's Magnetism in 1909, 1914, and 1919, with only slight changes in the original text

So much progress has been made since 1902 in the study of the earth's magnetism that the 1902 publication no longer gives a satisfactory picture of the present state of our knowledge of the subject, and this new publication is intended to supersede it and bring the information up to date

To begin with, the practical importance of a knowledge of the earth's magnetism is pointed out, the fundamental properties of a magnet are given, and the nature of the earth's magnet field is explained There follows a historical sketch of the development of our knowledge of the loadstone, the invention of the compass, and the discovery of the facts of the earth's magnetism The methods and instruments used in the field and at observatories for measuring the earth's magnetism and its variations are described, and the present extent of our accumulated data is given Finally, the theories which have been advanced to account for the earth's magnetism and its changes are outlined, and its relations to other phenomena are touched upon

Much of the historical material has been taken from the 1902 publication Detailed reference to original sources of information is not considered necessary Benjamin's Intellectual Rise in Electricity, published in London in 1895 and republished in New York in 1898 under the title "History of Electricity," was used freely by Bauer, and the writer has found the Bibliographical History of Electricity and Magnetism, by P Fleury Mottelay (London, 1922) of great assistance Mottelay's English translation of Gilbert's De Magnete and Dr G Hellmann's reproduction in 1898 of the very rare writings on the earth's magnetism prior to 1600 have made it possible to get first hand information regarding those important documents Additional information regarding the early history of the compass was obtained from the investigations of G Hellmann, A Wolkenhauer, P Timoteo Bertelli, and W van Bemmelen

IMPORTANCE OF A KNOWLEDGE OF THE EARTH'S MAGNETISM

Before the discovery of the directive property of the loadstone and the invention of the compass the traveler on land or at sea had to determine his direction of travel from known landmarks or the heavenly bodies, when they were not visible he was at a loss to know which way to go From this it resulted that the early explorers at sea did not venture far from land for fear that they might lose their way However, by following along the coast of Africa they eventu-

ally reached India and China With the introduction of the compass everything was changed Here was something to give direction, regardless of darkness, clouds or mist Adventurous spirits, like Columbus and Cabot, set boldly forth to find the unknown lands beyond the trackless ocean Their confidence in the compass was shaken for a time when they found that it did not in general point true north, but after safe return from voyages to the new world, confidence was restored, and exploration advanced very rapidly

Now practically every vessel of every description is equipped with one or more compasses, and the courses to be sailed from port to port are accurately laid down, for coastwise as well as for transoceanic travel Even the limited number of steamers equipped with gyro compasses carry magnetic compasses also for use in emergency

The surveyor's compass was one of the earliest forms of surveying instruments and for nearly all of the early land surveys in the United States the boundaries were defined in the deeds by compass bearings Even at the present time it is in general use where land values are low and more accurate and expensive methods are not justified

For the traveler in unexplored regions the compass is still indispensable, and the not infrequent reports of persons being lost in forests of small extent show that it is a wise precaution to take a compass for even such short departures from the beaten path

The compass is as necessary to the aerial navigator as to the mariner, and a special form of instrument has been devised for his use

The location and development of deposits of magnetic iron ore and other investigations of the geologist are aided by a knowledge of the facts about the earth's magnetism and the use of instruments for measuring it

The transmission of messages by telegraph and cable is frequently interrupted by currents of electricity in the earth, and electricity in the air has a material effect on the transmission of radio waves and these electrical manifestations are in turn closely allied with the earth's magnetism and its fluctuations

With so many matters of everyday occurrence directly affected by the earth's magnetism, it is very important that we should find out all we can about it, how it is distributed over the earth's surface, how it changes from hour to hour and from year to year, how it originated and what causes it to change, how it is related to earth currents, atmospheric electricity, solar activity, and other allied phenomena [1]

PROPERTIES OF MAGNETS

A piece of iron or steel which has the property of attracting iron or steel is called a magnet Loadstone, or magnetic oxide of iron, possesses this property in nature, and it is therefore called a natural magnet An artificial magnet may be made out of any piece of iron or steel by subjecting it to suitable treatment There are other so called magnetic bodies, such as nickel and cobalt, which are attracted in lesser degree by a magnet and which are susceptible of magnetization

It will be found by trial that there are two places in a magnet, one near each end, at which the attraction is greatest, and that there is a neutral line near the middle where the effect of the attraction be

comes zero For most purposes the attractive force of a magnet may be considered as concentrated at two points, one in each region of maximum attraction These points are called the poles of the magnet, and the line joining them is its magnetic axis A magnet suspended with its axis horizontal and free to turn about a vertical axis will take up a definite direction approximately north and south The pole near the north seeking end is called the north pole of the magnet, the one near the south seeking end the south pole

If the north pole of another magnet be brought near to the north pole of the suspended magnet it will be repelled, if it be brought near the south pole it will be attracted, that is, like poles repel, unlike poles attract each other

The space surrounding a magnet through which its influence extends is called its magnetic field At every point in the field the magnetic force exerted by the magnet has a definite strength and direction

If a piece of soft iron be placed in contact with, or near, one pole of a magnet, it will become magnetized and acquire the property of attracting other iron This is called magnetization by induction When the iron is removed from the magnet it will lose this property The end of the piece of iron nearer to the magnet acquires opposite polarity to that end of the magnet We now see that the attraction of a magnet for a magnetic body follows the same law that applies to the action between two magnets Like poles repel, unlike poles attract When a magnetic body is brought near the north pole of a magnet the part nearest the magnet becomes a south pole by induction and is attracted by it The part farthest away from the magnet becomes a north pole by induction and is repelled by the north pole of the magnet As the former is nearer the magnet than the latter, the resultant effect is an attraction In the same way when a magnetic body is brought near the south pole of a magnet, the part nearest the magnet becomes a north pole by induction, and is attracted as before, that is, induction precedes attraction

It is found that magnets gradually lose their magnetism with time, but at a diminishing rate Magnets are now usually made of a special grade of steel which has a high degree of retentivity, and the rate of loss is small

A magnet loses strength when heated, but regains it when cooled, provided it was not heated too hot A magnet heated red-hot loses its magnetism, and for the time being ceases to be a magnetic body When it is cooled it again becomes a magnetic body, but it does not regain its magnetism

THE EARTH S MAGNETISM

The earth acts like a great spherical magnet, and like a magnet it is surrounded by a magnetic field, and the measurement of the earth's magnetism at any place consists in determining the direction and intensity of that field

A magnet suspended in such a way as to be free to turn about its center of gravity would take a position with its magnetic axis directed along the lines of forces of the earth's magnetic field As it is practically impossible to suspend a magnet in that way, it is usual to determine the direction of the earth's magnetic field by

means of two magnets, one constrained to turn about a vertical axis, giving the direction in the horizontal plane (compass needle), and the other constrained to turn about a horizontal axis, giving the direction in the vertical plane (dip needle)

The magnetic meridian at any place is the vertical plane fixed by the direction of the lines of force or the direction of the compass needle at that place

The magnetic declination, *D*, is the angle between the astronomic meridian and the magnetic meridian, and is considered east or west, according as the magnetic meridian is east or west of true north Declination is often called variation of the compass or simply variation

The dip or inclination, *I*, is the angle which the lines of force make with the plane of the horizon

Instead of measuring the total intensity, *F*, of the earth's magnetic field, it is usually more convenient to measure its horizontal component, *H* These three quantities, declination, dip, and horizontal intensity, are usually spoken of as the magnetic elements, and from them the total intensity and its component in any direction may be computed by simple formulas

The so called magnetic poles of the earth are those points on its surface at which the dip needle stands vertical and toward which the compass needle points throughout the adjacent region The north magnetic pole is approximately in latitude 71° N and longitude 96° W, and the south magnetic pole in latitude 73° S and longitude 156° E It must be borne in mind that these magnetic poles have not the characteristics of the poles of a bar magnet If they had there should be an enormous increase in the total intensity when approaching them, which is not the case They are not even the points of maximum intensity, there being four areas, two in each hemisphere, where the total intensity is greater A bar magnet within the earth which would produce effects approximating those observed at the surface would have its poles nearly coincident

A piece of iron in the earth's magnetic field becomes magnetized by induction in the same way as when placed in the field of a magnet This fact is of the greatest importance to navigation in modern ships, since the iron which enters so largely into their construction becomes magnetized by induction and has a disturbing effect on the compass, and every time that the ship changes its direction its magnetism changes and the effect on the compass changes

EARLY HISTORY OF THE COMPASS

DISCOVERY OF THE LOADSTONE AND ITS PROPERTIES

At what date the properties of the loadstone first became known to man has not been definitely determined Its property of attracting iron was certainly known to the Greeks toward the close of the seventh century B C, as it is mentioned by Thales, who lived from 640 to 546 B C Some writers credit the Greeks with the use of the loadstone to direct navigation at the time of the siege of Troy, on the basis of a passage in Homer's Odyssey, but the reference seems too vague to justify such a conclusion The origin of the word magnet

is not well established, but it probably came from the place where the loadstone was first found (in the hills of Magnesia)

According to Bertelli, a careful examination of the writings of more than 70 Greek and Latin authors, covering the period from the sixth century B C to the tenth century A D, failed to find any mention of the directive property of the loadstone, or any suggestion from which one might conclude that this directive property was used either in navigation, astronomy, or surveying during that long period of time, though there are numerous descriptions of voyages and storms at sea where mention of the compass would be expected, if it had been in general use at the time Apparently the only facts about the loadstone which were known at that time were its property of attracting iron and of communicating that attractive power to iron That the property of polarity was unknown before the tenth century is indicated by the fact that Pliny and subsequent writers explained the phenomena of attraction, repulsion, and neutralization of magnetic action by ascribing them to three supposedly different minerals, magnete, teamede, and adamas Another circumstance supporting the conclusion that the compass was not used in the Mediterranean before the tenth century is the fact that all the early descriptions of it which we have (by Neckam, Guyot, etc, late in the twelfth century) speak of it as a new and wonderful thing

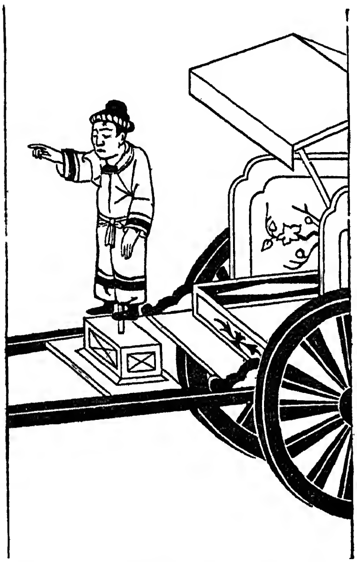

FIG 1—Japanese south pointing cart

There seems to be no doubt that the directive property of the magnet was known to the Chinese before the beginning of the Christian era Some writers go so far as to say that it was known as early as 2634 B C According to Klaproth a quaint legend relates that in the reign of Ho ang ti the Emperor's troops attacked some rebels led by Tchi yeou, on the plains of Tchou lou Finding that he was getting the worst of the conflict, Tchi-yeou raised a great smoke in order to throw the ranks of his adversary into confusion Ho ang ti was equal to the occasion, however, and constructed a chariot which indicated the south and thus was enabled to pursue the rebels and take Tchi yeou prisoner Benjamin considers this legend as clearly mythical Ho ang-ti was probably the outstanding figure of early Chinese history, the founder of the Chinese Empire, and it would not be surprising if knowledge and acts were ascribed to him which really belonged to a much later epoch

In various Chinese writings there are descriptions of the so called "south pointing carts" (tchi nan), and Humboldt is authority for the statement that they were in use as early as 1110 B C The south-pointing cart had mounted in front a pivoted figure with an outstretched arm A magnet was so placed in the figure that the

arm would always point south This device was in use in China as late as the fifteenth century of the Christian era and was introduced into Japan in the seventh century

There is also mention in Chinese books, now generally accepted as authentic, of the early use of a rude compass with a floating needle In a work entitled "Mung khi pi than," which appeared toward the end of the eleventh century of the Christian era, occurs the following remarkable passage

> The soothsayers rub a needle with a magnet stone so that it may mark the south however it declines constantly a little to the east it does not indicate the south exactly When this needle floats on the water it is much agitated The needle can also be balanced on the finger nail or on the edge of a cup but these being hard, the needle is unstable and slips easily It is better in order to show its virtues in the best way to suspend it as follows Take a single filament from a piece of new cotton and attach it exactly to the middle of the needle by a bit of wax as large as a mustard seed Hang it up in a place where there is no wind Then the needle constantly shows the south but among such needles there are some which being rubbed indicate the north Our soothsayers have some which show south and some which show north Of this property of the magnet to indicate the south no one can tell the origin

The intention of the Chinese author apparently was to point out the three methods of supporting a compass needle First, by floating it on the surface of a liquid, second, by pivoting it on some hard substance, and, third, by suspending it with a slender fiber

Considering all the available evidence, it seems probable that the attraction, polarity, and directive property of the loadstone were discovered independently in China and Europe The number of points of the early Chinese compass was 24 instead of 32, they reckoned from the south instead of from the north, the form of the Chinese instrument was different from that developed in Europe and had a very short, thin needle All efforts to account satisfactorily for the spread of the knowledge of the properties of the loadstone from eastern to western nations, or vice versa, have thus far failed

The names given to the magnet in other countries are suggested, as a rule, by one of its properties, as attraction for iron (French, aimant, Spanish, iman), directive property (English, loadstone, Icelandic, leidersteen, Swedish, segelsteen, German, siegelstein), hardness (Roman, adamas, Old English, adamant) The Italian form, calamita, may be derived from the method of supporting the magnet in the early form of compass, namely, on a bit of reed (calamo) floating in a vessel of water

The nature of the attraction for iron by the magnet was variously explained by the early Greek writers "Iron gives it life and nourishes it," "A certain appetite or desire of nutriment that makes the loadstone snatch the iron," "Humidity in iron which the dryness of the magnet feeds upon," "On the surface of the magnet there are hooks and on the surface of the iron little rings"

In addition to the physical properties of the loadstone recognized at the present day, curative properties for all sorts of maladies were ascribed to it in the Middle Ages, just as such properties were later ascribed to electricity Toothache, gout, dropsy, hemorrhage, and convulsions were among the many complaints which it was said to relieve, and even disputes between husband and wife came within the scope of its magic powers

On the other hand, a common belief which prevailed for many centuries was that a magnet would lose its directive property if rubbed with garlic, and mariners were charged not to eat onions or garlic lest the odor "deprive the stone of its virtue by weakening it and prevent them from perceiving their correct course"

INVENTION OF THE COMPASS

There seems to be no doubt that the Chinese were the first to use a form of compass in land journeys and in the orientation of buildings The passage from Mung khi pi than already cited shows that they had compasses with floating needles as early as the beginning of the twelfth century, and some writers maintain that they were in use centuries earlier Klaproth, who made a special study of the early history of the compass, found "No indubitable use" of the compass in navigation by the Chinese until toward the end of the thirteenth century

The earliest definite mention of the use of the compass in Europe occurs in a treatise entitled "De Utensilibus," written about the end of the twelfth century by an English monk, Alexander of Neckam In another book, De Naturis Rerum, he writes "Mariners at sea, when through cloudy weather in the day, which hides the sun, or through the darkness of the night they lose knowledge of the quarter of the world to which they are sailing, touch a needle with a magnet which will turn around until, on its own motion ceasing, its point will be directed toward the north"

At about the same date Guyot de Provins, minstrel at the French court, in a politico satirical poem entitled "La Bible," refers to the use by sailors of the compass with floating needle Other writers of the thirteenth century who speak of the use of the compass are Jacobus de Vitry, Cardinal of Ptolemais in Syria, Raymond Lully, of Majorca, Vincent de Beauvais, a crusader, Roger Bacon, a Franciscan Monk of Ilchester, Brunetto Latini, a celebrated Florentine encyclopedist, and the poet Dante Brunetto speaks of the compass as likely some time to be useful at sea, but adds "No master mariner dares to use it, lest he should fall under the supposition of being a magician, nor would even the sailors venture themselves out to sea under his command if he took with him an instrument which carries with it so great an appearance of being constructed under the influence of some infernal spirit"

It is to Pierre Pelerin de Maricourt, usually referred to as Petrus Peregrinus, that we owe what is probably the first European treatise on the magnet and the earliest known work on experimental physics. According to Roger Bacon, a contemporary, Peregrinus was the only man besides Master John of London, who at that period could be deemed a perfect mathematician and was one who understood the business of experimenting in natural philosophy, alchemy, and medicine better than anyone else in western Europe

Peregrinus was a native of Maricourt, a little village in Picardy, France, and his appellation Peregrinus indicates that he had taken part in the Crusades He was a partisan of Charles of Anjou and was with him at the siege of Lucera in southern Italy at the time (August, 1269) of writing his famous letter to his friend and neigh

bor, Sygerus de Foucaucourt—Epistola Petri Peregrini de Maricourt ad Sygerum de Foucaucourt, Miletem, de Magnete

In this epistle he gave a clear and concise statement about what was then known regarding the magnet and its properties, which he had evidently tested experimentally He conceived and made use of a spherical loadstone "in the likeness of the heavens," the progenitor of Gilbert's terrella, and with its aid devised methods for locating the poles, and found that at the poles a short piece of a needle would stand perpendicular to the surface of the stone He must also be credited with discovering the fact that when a magnet is broken into a number of pieces each piece will be a magnet, and with devising the methods of touch and rubbing for reversing the polarity of a needle

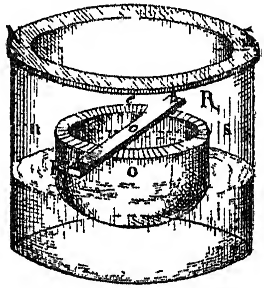

Fig 2—Floating compass used by Peregrinus (1269)

In the second part of the letter he described improvements of the compass (1) by the substitution of a pivoted needle for one floating in water, and (2) by the graduation of the rim of the circular bowl so that the azimuth of any heavenly body might be measured more easily and with greater accuracy

It will be noticed that Peregrinus had in his improved compass all the devices needed to ascertain whether the magnetic needle pointed precisely to the north or not As he reached the conclusion that the poles of the magnet receive their power from the poles of the world and noted that the direction of the magnet is not toward the mariner's star, since that star is always out of the meridian except twice in each complete revolution of the firmament, it seems safe to assume that the needle did not at that time point far from true north at the place where he made his experiments

Peregrinus proposed the use of a magnet in the construction of a perpetual motion machine, though Gilbert doubts whether the idea was original with him He was certainly not the last to work along

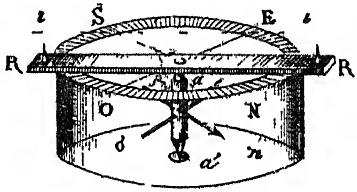

Fig 3—Double pivoted compass invented by Peregrinus

that line, as the idea has persisted in one form or another to the present day

With only a few manuscript copies of the letter of Peregrinus, knowledge of its contents could hardly have become very widespread, and some of the facts about the magnet which it contained were later discovered independently by others Up to modern times there was a persistent tradition that the mariner's compass was invented by Flavio Gioja, of Amalfi, Italy, about the year 1302 Bertelli made a very thorough investigation of the origin of this tradition and found nothing to indicate that it was founded on fact The

first writer to refer to it was Flavio Biondo, who, about 1450, made a first attempt at a history of Italy, and the name "Flavio" appears to have been introduced as the name of the reputed inventor by subsequent writers who quoted from this work of Flavio Biondo

It may be that one of the early Chinese compasses with floating needle was introduced into the Mediterranean by the Amalfians There appears to be no direct evidence on this point, but as the Amalfians were very enterprising and were permitted by the Arabian Government to traffic with the extreme east, it does not seem improbable that on some voyage a compass was brought home as a curiosity In any case, while it can not be definitely stated that this man invented the compass or that that man was responsible for certain modifications, it seems reasonably certain that the Amalfians should be credited with improving the compass by the substitution of a pivoted needle for the floating one and by the addition of the graduated compass card or "rose of the winds" attached to the needle and moving with it

COMPASS CHARTS

With the improvement of the compass it became possible for the mariners to determine with greater accuracy the direction from one port to another, and the construction of charts began to develop The early charts of the Mediterranean coasts of the fourteenth and fifteenth centuries were oriented by compass, as at that time the fact that the compass needle does not in general point true to the pole had not become known and it was believed that compass directions were also true directions

The earliest of these charts were by Marino Sanuto, between 1306 and 1324, the best, however, are those in the atlas of Andrea Bianco of Venice, which bears the date 1436 This atlas was subjected to a critical comparison with modern charts by Oscar Peschel He found that in spite of the crude appliances in use at that date, the distances from place to place harmonized in a most remarkable manner with later, more accurate, determinations, but the places were not always in their proper relations as regards latitude and longitude, the departures therefrom being quite systematic This was more noticeable in the latitudes because of the greater distances involved, places at the west end of the Mediterranean being shown too far north with reference to those at the east end

As the charts were based on compass directions, this systematic departure from the true directions indicates that the direction shown by the compass at that time differed by an appreciable amount from true north By measuring the angle through which one of these charts had to be turned (about Rome as a center) in order that the places would fall in their proper geographic relations, Bauer found that the magnetic declination at Rome was about 5° E in 1436, or more probably before that date, as the charts were undoubtedly constructed from data obtained during many years prior to the date of publication

In later years, after the fact of the magnetic declination became known, it became the practice in some localities to place the needles at such an angle to the compass card that the compass would give true bearings instead of magnetic bearings in the particular locality

in which it was to be used Thus Norman, in his book, The Newe Attractive, published in London in 1581, says that he finds in Europe five sorts of compasses, depending upon the locality in which they were used Those made in Italy gave the correct magnetic bearings, as a rule, presumably because the magnetic declination was small in the Mediterranean, but in Holland and Denmark the wires were set three quarters of a point or sometimes a whole point "to the east ward of the north of the compass," and in compasses for use in France, Spain, Portugal, and England the wires were most commonly set at half a point, and by these compasses the charts of the coasts of those countries as well as of the East and West Indies were made In Russia still another angle was used

Norman goes on to say

> And the mayster or maryner sayling by these compasses of sundry sorts may thereby fall into great perill and the reason is because that of long time these compasses have been used and by them the marine plats have been described of sundry sortes every one according to the compass of that country If then he take not the compasse of the same setts or making that the plat was made by then his carde or plat will show him one course and the compasse when he thinketh he goeth well will carry him another way

DEVELOPMENT OF THE MODERN COMPASS

The compass in the form developed by the Amalfians probably continued in use for many years without material modification At what time a special mounting for the compass was provided so that the compass bowl as well as the compass card would remain horizontal in spite of the rolling and pitching of the ship is not known, but the first printed description of the cardan suspension appeared in 1604 This form of universal joint, now in such general use, made possible greater accuracy in measuring the compass bearing on any object, whether terrestrial or celestial, and paved the way for the introduction of the azimuth circle and other aids to the use of the compass

With the introduction of iron and steel in the construction of ships it was found not only that the direction indicated by the compass was different for every heading of the ship but also that the compass card with a single needle was so easily set in motion swinging back and forth that it became difficult in rough weather to make an accurate reading This latter difficulty was overcome first by the substitution of a number of parallel magnets attached to the compass card symmetrically on both sides of the center line, in place of the single magnet, and later by the design of the liquid compass, in which the compass bowl is filled with liquid so that the compass card nearly floats and rests only were lightly on the pivot

The disturbing effect of the magnetism of the ship can be determined for each heading of the ship and allowance made for it, but when the amount becomes great, as it does in ships made largely of iron or steel, this method becomes inconvenient and does not yield sufficient accuracy To meet this difficulty there has been developed a method of counteracting the effect of the ship's magnetism so that the deviations will be small, "compensation of the compass," as it is called It is based on the general principle that the effect of the iron and steel of the ship acting at various distances may be balanced by magnets and soft iron suitably placed near the

compass Before the general use of steel in ship construction, the disturbance was due mainly to magnetism induced in the iron of the ship by the earth's magnetism Poisson made a study of this phase of the problem and in 1824 published a paper on the subject which has formed the basis for subsequent investigations of the theory of compass deviations

With the more general use of steel there was added to the induced magnetism the more or less permanent magnetism acquired by the steel either during the construction of the ship or afterwards The system of compensation finally evolved therefore provides for the use of both permanent magnets and soft iron, the part of the ship's magnetism which changes with change of heading being balanced by soft iron spheres and the part which remains constant with change of heading being balanced by the permanent magnets The compass is mounted in a binnacle (fig 4) to which the compensating devices are attached For further information on the subject the reader is referred to Special Publication No 96 of this bureau, entitled "Instructions for the Compensation of the Magnetic Compass," by N H Heck and W E Parker

In large all steel ships, particularly armored war vessels, the effect of the ship's magnetism on the compass is excessive, and the difficulty of securing and maintaining satisfactory compass compensation is very great Fortunately the development of the gyrocompass has made it possible to substitute it for the magnetic compass under such conditions

DISCOVERY OF THE MAGNETIC DECLINATION AT SEA

Benjamin in his Intellectual Rise in Electricity says

> The tendency of the magnetic needle to depart from the true north appears to have been observed by the Chinese geomancers in the compasses used by them long before any marine use of the instrument was made A so called life of Yi hing a Buddhist priest and imperial astronomer undertakes to show that the variation in the eighth century was nearly 3 west of south Later we find the geomancers adding special circles of symbols to the compass card such as a circle of 9 fictitious stars a circle of 60 dragons and so on and among these circles of points especially constructed to allow for variation This was done in the year 900 by Yang Yi when the variation was 5 15 east of south and again three centuries later when it had increased to 7° 30 in the same direction

In the passage from Mung khi pi than, already cited, it is stated that the south end of the needle constantly declined a little to the east (toward the end of the eleventh century)

In another book of about the same date it is stated that if the needle be made to float on water by means of a bit of reed it will show the south, but always with a declining toward the point "ping" Ping is the point 15 E of S Some writers contend that this and similar passages indicate that the fact that the compass needle does not in general point exactly to the pole of the heavens was known to the Chinese several centuries before its discovery by Columbus It should be noted, however, that translators are not agreed as to the proper rendering of the passage from Mung khi pi than, and the version given above is not altogether clear, so that there is some doubt as to whether it correctly represents the statements of the author

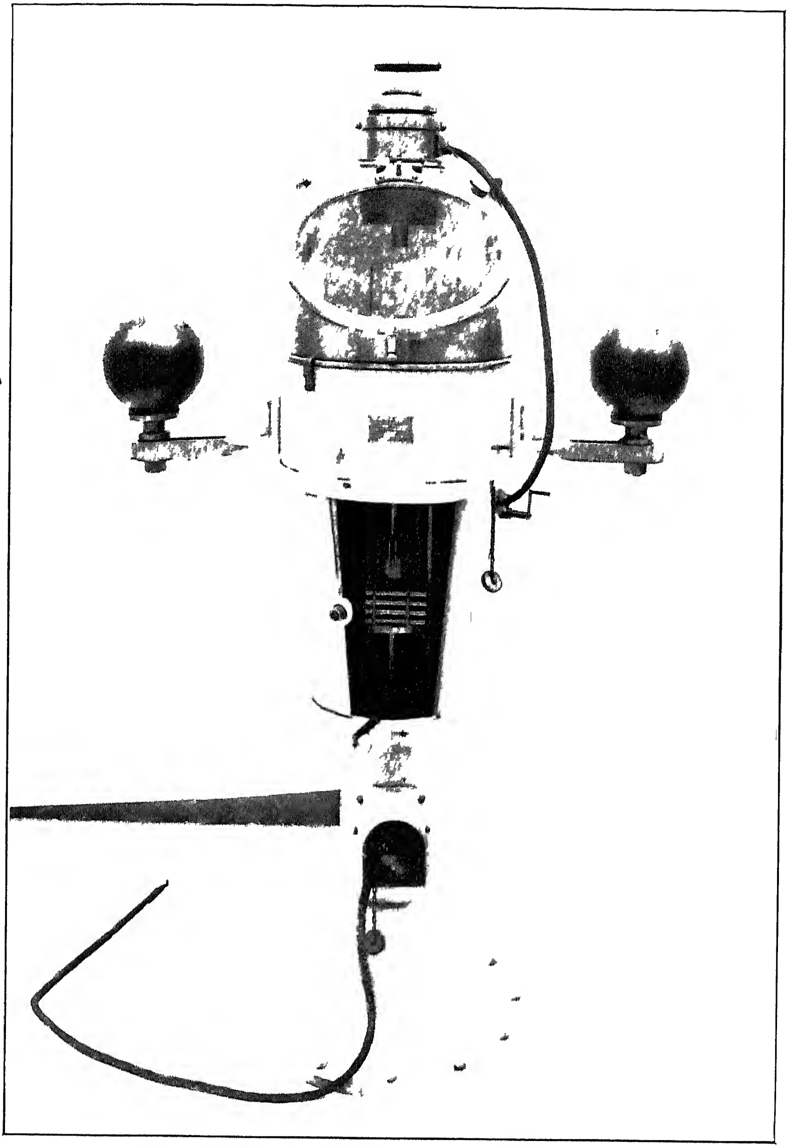

Fig 4—BINNACLE UNITED STATES NAVY TYPE

Bertelli points out that if the Chinese had known of the magnetic declination as early as the twelfth century it is reasonable to presume that the knowledge would have been handed down from generation to generation We find, however, that when, at the beginning of the seventeenth century, the Jesuit mathematician and astronomer, Matteo Ricci, and some of his fellow missionaries were allowed by the Emperor of China to take part in the Tribunal of Mathematicians, it was with great difficulty and only by ocular demonstration that they were able to convince the Chinese scientists that the magnetic and astronomic meridians are not coincident At that time the declination at Peking was about 2 W, as determined by Ricci Nearly two centuries later Amiot found that the Chinese still used that value of declination in placing their sundials, showing that the knowledge of the fact was preserved for two centuries after its demonstration by Ricci

Coming now to Europe, Columbus is credited with the discovery of the fact that the compass needle does not in general point true to the pole and that it changes its direction as it is carried from place to place On his first voyage he sailed from Palos to Gomera, one of the Canary Islands, and then laid his course due west, leaving on the evening of September 8, 1492 Our knowledge of the voyage is based on an abridged narrative written by Las Casas, a contemporary of Columbus, who had before him the original journals of Columbus, his map of the first discovery, and many letters and documents now lost In this narrative of the voyage it is stated that on the evening of September 13 the needle varied to the northwest and the next morning about as much in the same direction On September 17 the pilots took the sun's amplitude and found that the needles varied to the northwest a whole point of the compass The seamen were terrified and dismayed without saying why The admiral discovered the cause and directed them to take the amplitude again next morning, when they found that the needles were true The cause was that the star moved from its place while the needles remained stationary

The statement regarding the westerly declination of the needle seems to be perfectly definite, but it is difficult to harmonize it with the other statements of the extract If the compass needles actually pointed west of true north between September 13 and 17, how did it happen that the needles were true again the next morning? Did Columbus change the compass card (as he is said to have done on an earlier voyage) in order to allay the fears of his sailors? Observations were apparently made on the sun at sunrise and sunset, but the "motion of the star" is given as explanation of the mystery It is to be regretted that Las Casas abridged in any degree the log book of this epoch making voyage, as there must always be some doubt as to the accuracy of his record

Fortunately we have additional evidence on the subject There appears to be no further reference to the declination of the needle during the remainder of the voyage However, in a letter to his sovereigns giving a narrative account of his third voyage Columbus wrote "I remarked that from north to south in traversing these hundred leagues from the said islands (Azores) the needle of the compass, which hitherto had turned toward the NE, turned a full quarter of the wind to the NW, and this took place from the time

we reached that line" Continuing, he says "For in sailing thence (from the Azores) westward the ship went on rising smoothly toward the sky and then the weather was felt to be milder, on account of which mildness the needle shifted one point of the compass, the farther we went, the more the needle went to the NW, the elevation producing the variation of the circle which the north star describes with its satellites"

Here again there is a positive statement that there was a change in the direction of the needle not long after leaving the islands and that the declination had been east at first This latter statement indicates that the existence of the magnetic declination was known before the time of Columbus Such may have been the case, but as the investigations of Van Bemmelen indicate that the declination at that time was probably between 3° and 5° E throughout the eastern Mediterranean (see fig 5), the change from place to place

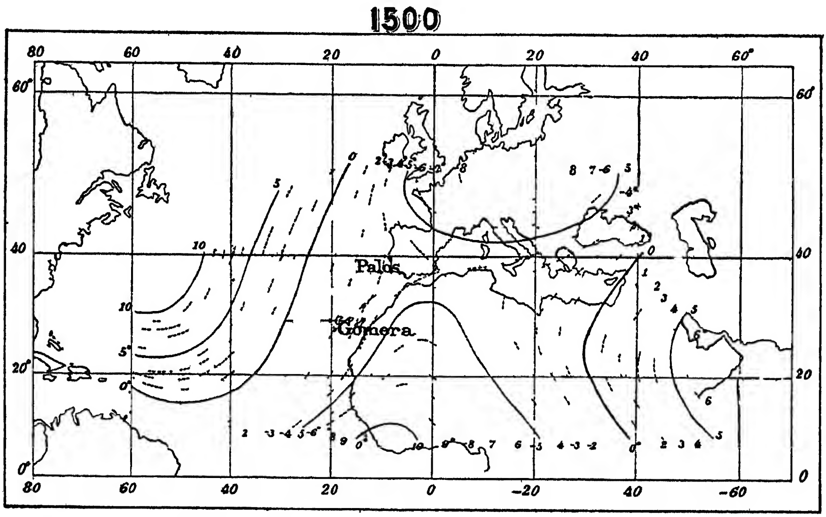

FIG 5—Lines of equal magnetic declination for 1500

would hardly be noticed, and the declination itself might indeed have been ascribed to instrumental error or error of observation, when the means available at that time for determining the declination are considered

In the journal of the homeward part of his second voyage (April, 1496) there were, according to Humboldt, passages indicating that Columbus attempted to make use of the observed direction of the compass needle as an aid to the determination of the ship's position in longitude In those days the means for determining elapsed time and distance sailed were very crude, half hour sand glasses for time and only an estimate of the speed of the ship based on previous experience Any device which seemed likely to give a more accurate determination of longitude was seized upon with avidity So we find that this idea of determining longitude from the magnetic declination was revived at intervals after Columbus's time until accurate timepieces became available

In spite of the discrepancies and ambiguities in the statements ascribed to Columbus, there seems to be no doubt that he must be credited with the discovery of the fact that the direction of the compass needle is different in different places and for the determination of the approximate position of a point on the agonic line, where the needle points true north.

As to the actual amount of declination encountered by Columbus in his first voyage, Schott attempted to reproduce the track followed by his ships from the known point of departure and the accepted point of arrival in the Bahama Islands and the distances and courses sailed according to the record in his journal. It should be noted that in spite of the recorded declination of "a whole point to the NW" (11¼°) on September 17, Columbus continued to lay his course due west by compass, except where stress of weather or indications of land led to a change. From these data Schott concluded that the declination could not have been more than 8° W. for any considerable portion of the voyage. He allowed a steady change from 3° E. at the Canary Islands to 8° W. on September 17, at latitude 27° 38′ and longitude 36° 30′, then holding this value until October 1 at latitude 25° 48′ and longitude 52° 14′, following with a gradual decrease to zero at the Bahama Islands. He estimated that Columbus crossed the agonic line between longitude 26° and 27°. If his conclusions are correct it is possible that the declination of a whole point reported by Columbus on September 17 may have represented the change of declination from what it had been in the Mediterranean and that this may be an indication that the fact of declination was not recognized before that time.

A second point in the line of no declination was found by Sebastian Cabot in 1497 or 1498 on his voyage to Labrador, in latitude 46° or 47° and on the meridian 110 miles west of the island Flores, one of the Azores. It is said that Cabot represented to the King of England that the variation of the compass was different in many places, and was not absolutely regulated by distance from any particular meridian, that he could point to a spot of no variation, and that those whom he had trained as seamen were particularly attentive to this problem, noting it at one time thrice within a short space.

This line along which the needle pointed exactly to the north, one point of which had been fixed by Columbus and another by Cabot, was believed to be a convenient line "given by nature herself" from which to reckon longitude, especially as it passed very near to the place from which longitude was then reckoned, and it figured prominently for many years in political geography as the line of demarcation between the rival kingdoms of Portugal and Castile. It is clear, however, by referring to any chart showing the lines of equal magnetic declination, that this line does not coincide with a true meridian, and it will be seen later that its position is not fixed but changes with lapse of time.

DISCOVERY OF THE MAGNETIC DECLINATION ON LAND

Knowledge of the discovery by Columbus of the change in the direction of the compass needle as he crossed the Atlantic was no

doubt soon communicated to other navigators, and additional information on the subject gradually accumulated as the result of other voyages of trade or exploration

The investigations of Hellmann indicate, however, that it was the construction of sundials that first brought this phenomenon to the attention of those on land Besides fixed sundials, the use of which may be traced back into the Babylonian Chaldean period, there were also in olden times portable sundials for travelers, the distinctive feature being a small compass, to be used no doubt for purpose of orientation Samples of these portable sundials are preserved in many of the museums of Europe, the oldest dating from 1451 The majority of them are of German origin, and it appears that as early as the middle of the fifteenth century Nuremberg was a recognized center for the manufacture of sundials provided with magnetic needles, which found a ready market not only in Germany but in other countries

One of the most famous of these compass makers, as they were called, was George Hartmann, who lived in Nuremberg from 1518 until his death, serving as vicar of the church of St Sebaldus He constructed such sundials in great numbers for persons of high rank, among others for Duke Albert of Prussia, with whom he corresponded This correspondence has fortunately been preserved for us In one letter Hartmann speaks of making eight compass sun dials of ivory and four smaller ones of boxwood, most of them designed for use in latitude 55°

Thanks to the searching investigations of A Wolkenhauer there have been brought to light three compass sundials constructed prior to 1500 The most important of these is in the Museum Ferdinandeum at Innsbruck This is a pocket sundial not much larger than a watch which bears the date 1451 It is made of copper (or bronze) gilded and decorated with a black enameled imperial eagle According to Hellmann, there appears to be no question that this sundial was made in Nuremburg, probably for Emperor Frederick III

The cardinal points are indicated on the rim of the compass box Across the bottom of the box there is a heavily engraved line, forked at one end, which it is believed indicates the direction of the compass needle at Nuremberg, about 11° east of true north, at the time the instrument was made A second specimen, in the Bavarian National Museum, dating from the year 1456, and very probably by the same maker, likewise has engraved on the compass a line making an angle of about 11° with the true north south line As the making of compass sundials had evidently reached a high state of perfection in the middle of the fifteenth century, Hellmann argues that this angle of 11° E may refer to an earlier date than 1451, as it is known that the same angle was used by Nuremburg compass makers well into the sixteenth century

We have no means of determining at what date the makers or users of these sundials became convinced that the failure of the compass needle to point exactly north was not due to imperfection of construction or to the peculiarity of the loadstone with which the needle was rubbed, but it is to Hartmann that we owe the first recorded determination of the magnetic declination on land Under date of March 4, 1544, he wrote to Duke Albert of Prussia that from

his own observations he had found the declination to be about 6° E at Rome and 10° E at Nuremburg and more or less at other places As Hartmann was living in Rome in 1510, his observation must refer to that date

Even before that date, as we have seen, the compass makers adopted the practice of placing a line on the sundial to indicate the angle between true north and the direction taken by the compass needle, and Wolkenhauer gives a valuable summary of the angles of the early compass sundials according to the country or place from which they originated Thus it has been possible from some of the old sundials which have been preserved to derive values of the magnetic declination for the date of their construction From the one shown in Figure 6, for example, an ivory sundial made by Hieronymus Bellarmatus in 1541 and found in the collection of the Prince de Conti, it is concluded that the declination was about 7° E in Paris in 1541

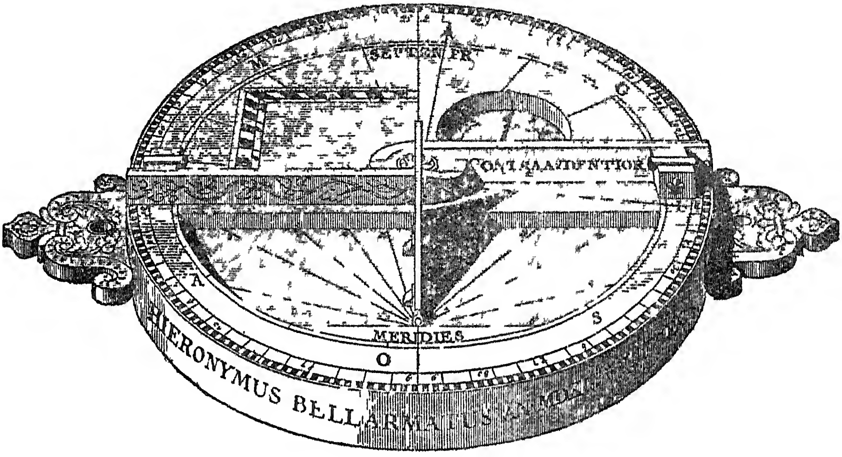

Fig 6 – Compass sundial 1541

EARLY METHODS OF DETERMINING THE MAGNETIC DECLINATION

The method first used was no doubt that of noting the magnetic bearing of the pole star, and this was probably the one employed by Columbus That no great accuracy could be attained in this way is self evident, and it is doubtful whether at first the motion of the pole star about the pole was recognized and taken into account

Felipe Guillen, a Sevillian apothecary, devised an instrument for a more accurate determination of the declination, which he called *brujula de variacion* and which he presented to the King of Portugal in 1525 With this instrument the magnetic bearing of the sun was noted at equal altitudes before and after noon, with the aid of the shadow from a stylus Half the difference of the bearings was the declination

The first book giving directions for determining the declination appears to be one by Francisco Falero, published at Seville in 1535 He gave three methods, all making use of the sun (1) Magnetic bearing of the sun at apparent noon, when the shadow of the stylus falls to the north, (2) Guillen's method of equal altitudes, and (3)

magnetic bearing of the sun at sunrise and sunset The wording of Las Casas's version of the journal of Columbus and the recorded fact that observations were made morning and evening suggest the possibility that the third method may have been used by Columbus

In 1537 Pedro Nunes improved Guillen's instrument by adding a device for measuring the sun's altitude and invented a new method for the determination of latitude at any time of day Infante Dom Luis of Portugal, who had received instruction in mathematics and astronomy from Nunes and had shown great interest in all nautical problems, presented such an instrument to Joas de Castro, commander of one of the 11 ships that sailed to the East Indies in 1538, and charged him to give it and the new methods a thorough test How completely Castro carried out his instructions is shown by the very full journals or log books in which he recorded all his nautical, magnetic, meteorologic, and hydrographic observations and notes on allied phenomena from 1538 to 1541, and which are undoubtedly the most valuable records of the kind made during the first half of the sixteenth century They include 43 determinations of the magnetic declination, notes regarding the instruments and methods, the deviation of the compass, magnetism of rocks, etc After reading the journals, Hellmann did not hesitate to pronounce Joas de Castro to be the most noteworthy representative of scientific marine investigations up to the close of the epoch of discoveries

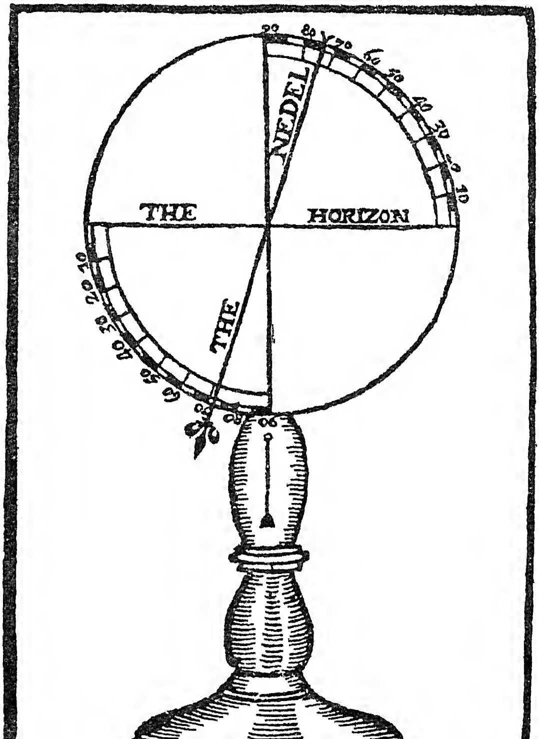

FIG 7—First dip circle (Norman's 1576)

The methods thus given such a thorough trial gradually came into general use among navigators, and we find them described by writers in Spain, England, and Holland as late as the end of the sixteenth century, but without mention of Guillen, Falero, or Nunes

DISCOVERY OF THE MAGNETIC INCLINATION

Although Hartmann, the Nuremburg maker of sundials, had noticed in 1544 that the north end of the compass needle tends to dip below the horizon, it was left for Robert Norman, of London, to devise an apparatus with a needle supported on a horizontal axis and actually measure the amount of dip In his book The Newe Attractive, published in 1581, Norman tells "by what means the rare and strange declining of the needle from the plane of the horizon was first found" Norman was an instrument maker who had had 18 to 20 years practical experience as a seaman In making compasses he noticed that it was always necessary to put small pieces of wax on the south end of the needle in order to balance it, although it had been perfectly balanced before magnetization He paid little heed to this fact, however, until he had occasion to make an instrument with a needle 6 inches long and was constrained to cut away some of the north end to secure a balance In doing this he cut it too short and spoiled the needle

Provoked by the necessity of doing his work over again ("hereby being stroken in some choller" as he says) Norman devised an instrument to determine how much the needle touched with the stone would decline, or what greatest angle it would make with the plane of the horizon With this instrument he measured the dip at London in 1576 and found it to be 71° 50′ The general character of the instrument is indicated by the sketch in Figure 7, copied from Norman's book

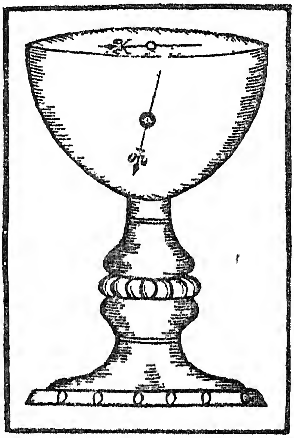

FIG 8—Norman's floating dip needle

This discovery upset the earlier beliefs that the needle was drawn toward some point in the heavens or toward some mass of loadstone near the North Pole Norman continued his investigations and proved experimentally that the force exerted on the needle by the earth's magnetism does not produce motion of translation but simply that of rotation To do this he first stuck a steel wire through a piece of cork of such size as to support the needle on the surface of a vessel of water Then he cut away the cork bit by bit until it would float the wire 2 or 3 inches below the surface At the same time he adjusted the position of the cork with respect to the wire so that the wire would lie horizontal After being rubbed by the stone the north end of the wire dipped below the horizon as the needle had done in the dip circle, but the supporting cork continued at the same depth as before (See fig 8)

He also weighed several pieces of steel wire before and after magnetization, using a "fine gold balance," and showed that no change of weight occurred, thus disproving the assertion made by some that the act of rubbing one end of the needle by the stone added to its weight

Norman concluded that the "point respective," or the point toward which the freely suspended needle was directed, lay somewhere in

the continuation of the line through the dipping needle, and that dip observations in other places would serve to fix the position of the point by intersections He ventured the opinion that the angle of dip would be found to change according to the distance from the "point respective"

In his book Norman called attention to the common practice of adjusting the compass card to correspond to the variation in the region where it was to be used, and the confusion which had resulted from the use of such compass in making maps

Annexed to later editions of Norman's book (if not to the first) appeared "A discourse of the variation of the compass," by William Borough, which explained several methods of determining the variation of the compass and gave directions for its use in navigation Borough called attention to the irregular distribution of the earth's magnetism, partly on the basis of his own experience as a navigator, and showed that the observed compass variations can not be explained by a magnetic north pole toward which the needle is directed

THE EARTH A GREAT MAGNET

The year 1600 is a memorable one in the history of the sciences of magnetism and electricity, for in that year appeared Dr William Gilbert's famous work De Magnete, giving the most complete summary of the properties of magnetic bodies up to that time, and containing his theory that the earth itself is a great magnet

Gilbert was born at Colchester, England, in 1540, and after graduating at St Johns College and serving there as mathematical examiner, he took up the study of medicine and received his degree in 1569 He is said to have practiced as a physician with great success and applause His skill attracted the attention of Queen Elizabeth by whom he was appointed physician in ordinary, and who showed him many marks of her favor, besides settling upon him an annual pension to aid him in the prosecution of his philosophical studies

Gilbert's early investigations were directed to the study of chemistry, but later he turned his attention to electricity and magnetism, his interest aroused perhaps by Norman's discovery of the magnetic dip and the publication of The Newe Attractive in 1581, for it is stated that Gilbert had been actively engaged in the study of magnetism for nearly 18 years before the appearance of De Magnete in 1600, so that he must have begun about 1582

Gilbert went about his investigations in a thorough and systematic manner The book itself shows his familiarity with previous writings on the subject, and it is said that he spent £5,000 on his experiments, "examining very many matters taken out of lofty mountains or the depths of seas, or deepest caverns, or hidden mines, in order to discover the true substance of the earth and of magnetic forces" He evidently had a collection of loadstones of various kinds coming from a number of different localities Gilbert, like Norman, was a thorough believer in the importance of experimentation, and he had no patience with the "conjectures and opinions of philosophical speculators of the common sort" Herein lies the great value of Gilbert's work on the properties of magnetic bodies, that nearly every conclusion drawn rests on experiments made over and over under slightly varying conditions He was not willing to accept the state-

ments of others until he had satisfied himself experimentally that they were correct

In connection with his conception of the earth as a great magnet Gilbert paid particular attention to experiments with a terrella, or spherical loadstone, and a very small pivoted magnetized needle (versorium) as long as a barleycorn His description of one terrella gives its diameter as 6 or 7 fingerbreadths, but he evidently had several

De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure, as the title indicates, was written in Latin, but an English translation by P Fleury Mottelay was published in 1893, and it is from that translation that the information here given has been derived Unfortunately Gilbert frequently made use of what he terms "words new and unheard of," besides attaching to many others a significance far different from that generally accepted at this day, so that the translator had difficulty in determining the exact meaning of some passages in the book

After giving the various kinds of loadstone, where they are found and their characteristics, similar information regarding iron, and noting their similarity, Gilbert sets forth his theory that the loadstone is the fundamental form of matter, that loadstone constitutes all but the outer shell of the earth and that the various forms of matter with which we are familiar are derived from loadstone by disintegration, that the earth, being a great loadstone, has poles and a magnetic equator, just as the terrella has its magnetic poles and a neutral line between, it takes a definite direction in space, just as the terrella takes a definite direction with reference to the earth, it rotates daily about its axis, just as the terrella turns under certain conditions Although most of Gilbert's reasons for considering the earth a great loadstone have since been discarded, his idea that the earth acts in much the same way as a spherical magnet was the starting point for the future development of the science of terrestrial magnetism

According to Gilbert's theory the compass needle should everywhere point in the direction of the true meridian Though he gave no table of values of the magnetic declination in De Magnete, he was evidently familiar with what was known of its distribution at that time and recognized the errors inherent in the instruments and methods then in use He explained the fact that the needle does not in general point true north by saying that the north end of the needle is drawn toward the land in the northern hemisphere and the south end in the southern hemisphere, because of the greater amount of loadstone in these more elevated portions of the earth's crust He supported this statement by experiments with a terrella on which irregular masses projected above the spherical surface At that time the declination was small in the interior of Europe and he was able to find a spot near the center of the raised mass on the terrella where the versorium showed no variation From this he concluded that declination was greatest near the borders of the land and decreased to zero in mid ocean and also in the middle of continents Later observations showed the error of his conclusions He was evidently familiar with the fact that the force directing the compass needle, the horizontal force, is greatest at the magnetic equator and

decreases toward the magnetic poles, as he gives that as the reason why the observed declinations are greater in higher latitudes than near the Equator, the needle being more susceptible to disturbing causes near the surface as the directive force becomes less

Although Gilbert probably had no observed value of dip outside of the one determined by Norman at London, he was able with his terrella to obtain a very good idea of the distribution of dip on a uniformly magnetized sphere (fig 9), showing the general characteristics of actual conditions on the earth, changing from no dip at the Equator to 90° at the poles, the change with change in latitude being more rapid near the Equator than near the poles He devised a graphical method for deriving the dip for any latitude, on the basis

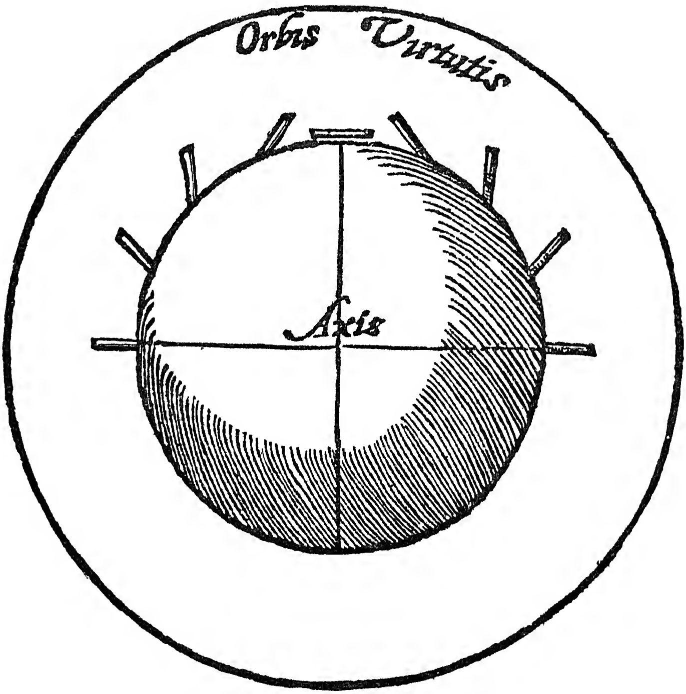

FIG 9—Orbis Virtutis (Gilbert)

of the earth being uniformly magnetized about its axis of rotation, which gave for the latitude of London approximately the same value as observed by Norman, and proposed to use dip observations as a means of determining latitude, designed an instrument for measuring the dip, and showed how it might be mounted on board ship for the purpose This proposal is surprising, for he shows in another part of the book that the irregularities in the distribution of the earth's magnetism make it impossible to use the declination as a means of determining longitude and he recognized the probability that there would be corresponding irregularities in dip, but he evidently thought they would be small

In Book II an explanation is given of the difference between the attraction exerted by electrified bodies, particularly amber, and that

exerted by the loadstone and other magnetized bodies The mutual action between loadstone and iron is gone into in great detail

In Book III, devoted to the directive property of the loadstone, its verticity, as Gilbert calls it, attention is called to the fact that a bar of iron may be magnetized without being rubbed by the loadstone, particularly if hammered while cooling, the direction of its verticity depending upon the direction in which it was held at the time, also that an iron bar fixed in a north and south direction for many years will become magnetized This latter fact was discovered on January 6, 1586 A piece of iron which for a long time had supported a terra cotta ornament on the tower of the church of San Agostino at Rimini was bent by the force of the winds and so remained for 10 years The friars, wishing to have it restored to its original shape, took it to a blacksmith, and in the smithy it was discovered that it resembled loadstone and attracted iron

Impressed with the fact that the earth as well as the loadstone exerts an influence at a distance, in spite of intervening bodies, Gilbert used the term "orbis virtutis" (fig 9) to denote the magnetic field of a magnet—the space surrounding a magnet through which its influence extends—apparently getting the idea from Norman, who spoke of the "vertue extending rounde about the stone in great compasse"

It gives an interesting side light on the times in which Gilbert lived to read the following statement in his book "And as the planets and other heavenly bodies, according to their positions in the universe and according to their configuration with the horizon and the earth, do impart to the newcomer (newborn infant) special and peculiar qualities, so a piece of iron, while it is being wrought and lengthened, is affected by the general cause, the earth" Evidently Gilbert accepted without question the tenets of the astrologers at the same time that he was subjecting the properties of the loadstone to repeated experiments

DISCOVERY OF THE SECULAR CHANGE OF THE MAGNETIC DECLINATION

The next noteworthy contribution to the science of terrestrial magnetism was the discovery of the change of the magnetic declination with time, by Gellibrand in 1634 Up to that time it had been supposed that the declination, though different at different places, was fixed and invariable at any one place, except that "by the break up of a continent," as Gilbert put it, it might suffer a change

Henry Gellibrand was a professor of mathematics at Gresham College He made a careful determination of the magnetic declination at Diepford, about 3 miles southeast of London Bridge, on June 12, 1634, and got the value 4° 06′ E Now Edmund Gunter, another mathematician of Gresham College, had found it to be 5° 56½′ E on June 13, 1622, and for 1580 Borough and Norman had found 11° 15′ E Gellibrand repeated his observations and then examined carefully the published observations of Borough, without making any material correction Clearly, therefore, the magnetic declination had changed by a considerable amount between 1580 and 1634.

Gellibrand announced his discovery in a book entitled "A Discourse Mathematical on the Variation of the Magnetical Needle, together with its Admirable Diminution Lately Discovered" He refrained from speculating as to the source of the change, "whether it may be imputed to the magnet or the earth, or both," saying that it must all be left to future times to discover

Gellibrand's discovery was of the greatest importance to all users of the compass No longer could the mariner feel confident that on visiting a distant port he would find the same value of declination as had been observed by previous navigators, nor could the land surveyor retrace the lines of an old compass survey without first finding out how much the declination had changed in the meantime

Since Gellibrand's time observations have shown that the dip and intensity of the earth's magnetic field are also changing with lapse of time, but the cause of the change is still a mystery

DISCOVERY OF THE DIURNAL VARIATION OF DECLINATION

It is related that in the year 1682 in the city of Louveau, Siam, Pater Guy Tachart, in the presence of the king, found that the magnet declination on successive days was 0° 16′ W, 0° 31′ W, 0° 35′ W, and 0° 38′ W, and after the lapse of a few days, values of 0° 28′, 0° 33′, and 0° 21′ were obtained It is probable that these observations were not all made at the same time of day and that the observed differences were due at least in part to the change in the direction of the compass needle which goes on from hour to hour throughout the day, and these may be considered the earliest observations to bring out that change

The credit of the discovery of the diurnal variation must properly be given, however, to a London mechanician and clock maker named Graham, who, after many hundred observations of the declination at various times of the day, made in 1722 a definite announcement of his discovery The discovery was later verified and amplified by Prof. Anders Celsius in Upsala with a needle made expressly for the purpose, and by a host of other investigators In fact the diurnal variation, because of its periodic character, has been a well tilled as well as a fruitful field of investigation

MEASUREMENT OF INTENSITY OF THE EARTH'S MAGNETISM

Graham also was probably the first to suggest that relative values of the intensity of the earth's magnetism might be obtained by noting the time of vibration of a compass needle, but there is no record of observations by him Frederick Mallet was the first one to make such observations, and he found, in 1769, the times of vibration to be the same at St Petersburg and a place in China In 1776 Jean Charles Borda, a French mathematician and astronomer, improved upon the work of Mallet and made observations with the needle of a dip circle mounted in the magnetic meridian during an expedition to the Canary Islands With the dip needle so mounted relative values of the total intensity may be obtained, whereas the vibration of the compass needle would give relative values of the horizontal intensity With the instruments then in use it is probable that greater accuracy was obtainable with the dip needle With the

development of an instrument with a magnet supported by a silk fiber much greater accuracy was possible with the horizontal magnet

Poisson was probably the first (1828) to conceive a method for making absolute determinations of the intensity, but it was left for Gauss to devise a practical method, the one in general use to day His first paper on magnetism, published in 1832, was devoted to this subject, and a few months later, working with Weber at Gottingen, he developed a magnetometer with fiber suspension for declination and absolute intensity observations In the same year he erected a magnetic observatory at Gottingen and later developed suitable instruments for measuring the variations of declination and horizontal intensity It is interesting to compare Gauss's bifilar variometer, having a magnet more than 3 feet long, weighing 25 pounds, and a suspension 17 feet long, with the modern instrument having a magnet an inch long, weighing only a fraction of an ounce, and a quartz fiber suspension less than a foot long

In 1838 Gauss published his famous paper "Allgemeine Theorie des Erdmagnetismus," in which he developed a potential formula in terms of spherical harmonics to represent the facts of the earth's magnetism as known at that time This has formed the basis for most of the mathematical discussions regarding the distribution of the system of forces required to produce the earth's magnetism, which have led to the conclusion that about 95 per cent of it is due to forces within the earth

This study of the earth's magnetism as a whole directed attention to the need of more accurate and more extended information regarding the distribution of the earth's magnetism over the surface With the assistance of Humboldt, Gauss succeeded in arousing the interest of scientists in other countries and developed one of the earliest examples of international cooperation for the study of a world-embracing natural phenomenon Magnetic surveys were undertaken and observers were sent to regions where magnetic observations had not previously been made, including the expedition of Ross to the vicinity of the magnetic south pole Soon after 1840 magnetic observatories were established at widely separated points to secure simultaneous data regarding the variations of the earth's magnetism Some of them were discontinued at the close of the limited period for which international cooperation had been arranged, but others continued in operation much longer, some (as the one at Toronto, Canada) even to the present day It is of interest to note that, thanks to the zeal of A D Bache, later superintendent of the Coast Survey, a magnetic observatory was operated at Girard College, Philadelphia, from 1841 to 1845, and that variation observations were made in Washington from 1840 to 1842 One of the observatories established by Russia was at Sitka, Alaska, and was in operation from 1842 to 1867 In spite of the inferior instruments then available, the operation of these observatories served to establish the principal features of the short period variations of the earth's magnetism

MAGNETIC SURVEYS

From that time on the importance of a knowledge of the earth's magnetism was recognized more and more, and one after another the civilized nations instituted magnetic surveys of their own posses

sions Great Britain took the lead with a survey of the British Islands between 1836 and 1838 This survey was repeated between 1857 and 1862, again in much greater detail between 1884 and 1892, and once more in less detail in 1914 and 1915 The work was extended to India, Canada, Australia, New Zealand, Egypt, and South Africa Nearly all European countries have now been surveyed magnetically in more or less detail Japan has made two detailed surveys

In the United States the magnetic survey of Pennsylvania and parts of adjacent States, by Alexander Dallas Bache, in 1840–1843, was the earliest response to the awakening of interest in terrestrial magnetism, if we except the scattered observations of Long, in 1819, Nicollet (1832–1836), Locke (1838–1843), and Loomis (1838–1841) The last named made the first general collection of results of magnetic observations in this country and prepared the first magnetic maps, covering the eastern part of the United States

When the Coast Survey was reorganized in 1843 the making of magnetic observations was included in its regular functions, and from that time on many magnetic observations were made, at first confined to the coasts, to supply the necessary compass data for its charts, but later extended to the interior States In 1899 it became possible to undertake a systematic magnetic survey of the country The general survey has now been completed and more detailed investigation of disturbed areas has been carried out to some extent To meet the needs of local surveyors, the work was based largely on the county subdivision of States, with a magnetic station at every county seat Most of the stations were marked in a permanent manner, so that they would be available for future use, but in a great many cases industrial developments incident to increase in population have put an end to their usefulness

At intervals of about five years observations have been repeated at selected stations distributed over the whole country, to keep track of the changes taking place in the earth's magnetism with lapse of time

The work has been extended to Alaska, Porto Rico, Hawaii, Philippine Islands, Guam, and the Canal Zone, and many observations have been made at sea on the vessels of the bureau in connection with their other surveying work

Recognizing the fact that only a small portion of the earth's surface is occupied by the civilized nations, and that it would be extremely difficult to secure governmental funds for work to be done outside a country's jurisdiction, Dr L A Bauer, who was in charge of the magnetic work of the United States Coast and Geodetic Survey from 1899 to 1906, presented to the trustees of the Carnegie Institution of Washington a plan for the establishment of a bureau for international magnetic research, including a world wide magnetic survey to supplement the work being done by other agencies This plan was approved, and the Department of Terrestrial Magnetism of the Carnegie Institution of Washington was established in April, 1904, and Bauer became its first director

With about three quarters of the earth's surface covered by water, it was evident that one of the most important features of a world magnetic survey should be a magnetic survey of the ocean areas

Some observations at sea had been obtained on the *Erebus*, *Terror*, and *Pagoda*, under Ross, in the fourth decade of the nineteenth century, on the *Challenger*, 1872–1876, the *Gazelle*, 1874–1876, the *Discovery* and *Gauss*, 1902–1904, but they covered only a very minute portion of the whole ocean, and most of them were old and lacking in accuracy

From experience gained with the vessels of the Coast and Geodetic Survey, Bauer had satisfied himself of the feasibility of making magnetic observations at sea with nearly the same accuracy as on land if a suitable vessel could be obtained His plan for the world survey, therefore, included as one of its principal features a magnetic survey of the ocean areas by means of a nonmagnetic vessel This work at sea was carried on successfully from 1905 to 1921, first on a chartered sailing vessel, the *Galilee*, and later on the *Carnegie*, a sailing vessel with auxiliary steam power, built for the purpose, so nearly free of magnetic material as to practically eliminate the need of taking account of deviation corrections

While this work at sea was carried on primarily for scientific purposes, it had great immediate practical value in that it provided the means for correcting the existing world magnetic charts, which were found to be seriously in error in some places because of the insufficient data on which they were based

At the same time that the work at sea was in progress magnetic observers have been sent to nearly all accessible regions where magnetic surveys were not being made under other auspices, and to some regions usually thought of as inaccessible Asia, Africa, South America, Central America, and Mexico have all been the field of these far reaching operations In some cases one season's work by an observer of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington was sufficient to stimulate local interest to a point where means were provided for continuing the work under local auspices

As a result of the general interest aroused, the making of magnetic observations became recognized as an important part of the work of an exploring expedition, and in this way much data has been secured in regions which would not ordinarily be reached This is particularly true of the polar regions The Ziegler expedition to Teplitz Bay in 1903 and 1904, Amundsen's work in the vicinity of the magnetic North Pole in 1903–1906, and along the north coast of Siberia in 1918–1921, and the work of MacMillan's two expeditions served to reduce materially the size of the magnetically unexplored region around the North Pole, while the various south polar expeditions, German, French, British, and Australasian, between 1902 and 1912, supplied a large amount of valuable information regarding magnetic conditions on the borders of the Antarctic Continent and served to locate the position of the south magnetic pole within narrow limits

As a result of this general activity there has been executed during the past 25 years a world magnetic survey covering practically the whole surface of the earth between latitude 70° N and 60° S, supplemented by the work in the polar regions referred to above Improved methods and instruments have added materially to the

accuracy of the results, and international comparisons of instruments have insured a greater homogeneity

Practically all of the results of these various magnetic surveys have been published in detail in one form or another by the organization doing the work Those of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington are contained in four volumes of Publication No 175 of that institution, covering the work on land to 1920 and the work at sea to 1916 Since 1903 the Coast and Geodetic Survey has published the results of its magnetic field work annually Special Publication No 44, United States Magnetic Tables and Magnetic Charts for 1915, contains the collected results of all observations made up to 1915, together with corresponding reduced values for January 1, 1915, and isomagnetic charts for that date Similar data for Alaska are contained in Special Publication No 63

FIELD INSTRUMENTS AND METHODS

While for most practical purposes it is sufficient to know about the magnetic declination—the variation of compass, as the navigator calls it—the determination of the other magnetic elements, dip and intensity, adds comparatively little to the time required for the occupation of a magnetic station, and without a knowledge of all three little progress can be made in a scientific study of the phenomenon of the earth's magnetism, its origin, why it changes, how it is related to other phenomena, etc Therefore practically all modern magnetic surveys have provided for the determination of the dip and intensity as well as the declination

Declination and horizontal intensity observations are usually made with the same instrument, a magnetometer, of which one type is shown in Figure 10 A hollow cylindrical magnet hangs in a horizontal position in a stirrup supported by a silk fiber or fine metal ribbon One end of the magnet is closed by a piece of plane glass on which two lines at right angles are engraved The other end is closed by a lens which makes it possible to point on the intersection of the lines with the reading telescope when the latter has been focused for distant objects A scale in the reading telescope permits direct observation of small motions of the magnet, and the whole instrument is mounted on the base of a theodolite with a horizontal circle on which may be read the angle between different pointings with the telescope

The magnetic declination at any place is the angle between the true meridian and the magnetic meridian at that place The true meridian may be determined by observations of the sun or Polaris Sometimes a true meridian line is marked on the ground by two monuments, but it is always more convenient to determine first the true bearing of some well defined prominent object, nearly in the horizon This is done by measuring the horizontal angle between the sun and the selected object and then computing the true bearing of the sun at the time of observation

The direction of the magnetic meridian is given by the suspended magnet, and the angle between that direction and the direction to the mark is the magnetic bearing of the mark Finally, the differ-

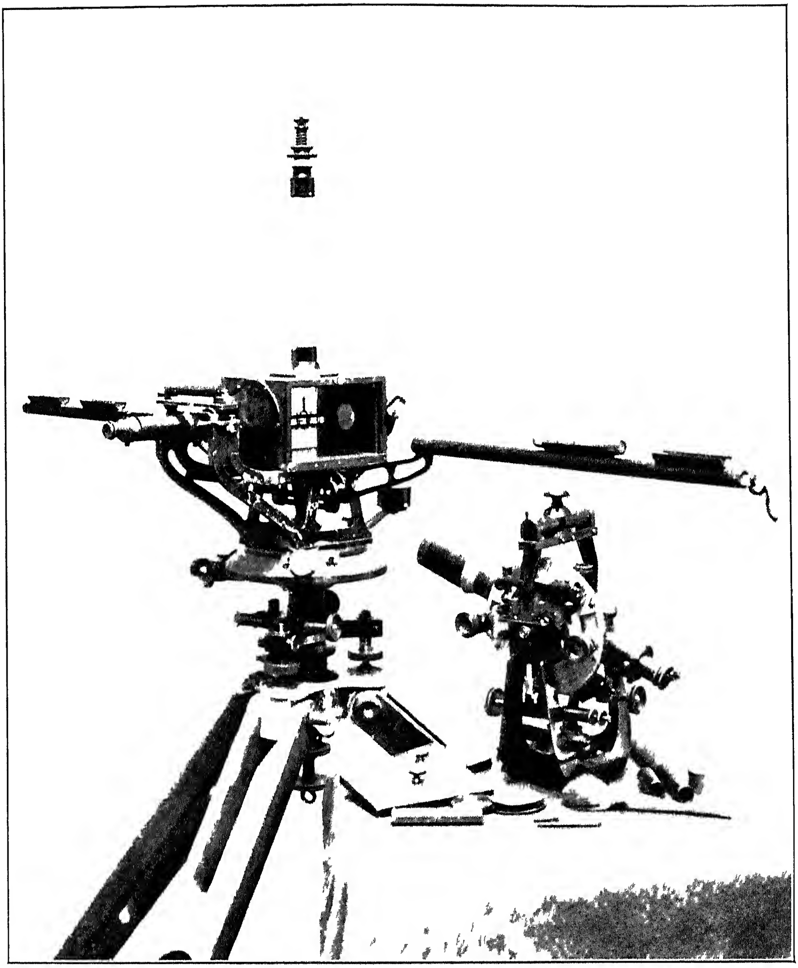

Fig 10 MAGNETOMETER COAST AND GEODETIC SURVEY PATTERN

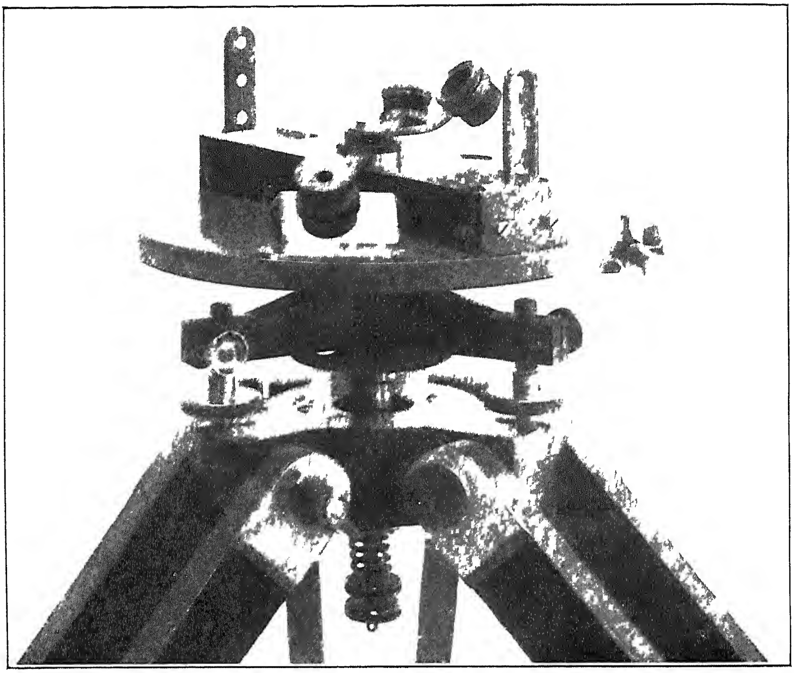

Fig 11 —COMPASS DECLINOMETER

ence between the magnetic bearing of the mark and the true bearing is the magnetic declination

Sometimes, when a magnetometer is not available, the declination is determined by means of a special form of compass called a compass declinometer, shown in Figure 11, in which a compass needle is mounted in a rectangular box with graduated arcs at the ends Peep sights are provided for pointing on the object used as a mark and the angle between the mark and the needle is read off on the horizontal circle of the instrument With the compass declinometer it is necessary to determine and allow for the index correction of the needle, just as in the case of the ordinary surveyor's compass, though the amount is usually small

For the determination of the horizontal intensity two operations are required, called oscillations and deflections When the magnet is suspended as for the determination of declination and is given a slight impulse the cross line on the glass in the end of the magnet will be seen to swing first to one side and then to the other of the position of rest, like a horizontal pendulum The time of oscillation depends upon (1) the dimensions and mass of the magnet, (2) upon the magnetic moment of the magnet, and (3) upon the horizontal intensity of the earth's magnetic field An increase in either (2) or (3) will cause a decrease in the time of oscillation

For deflection observations the magnetometer is provided with a bar placed at right angles to the line of sight of the reading telescope, on which the magnet used during oscillations is placed as a deflector while a shorter magnet is suspended in the stirrup The suspended magnet will be turned out of the magnetic meridian by an amount depending upon the relative strength of the deflecting magnet and the horizontal intensity This operation thus serves to determine the ratio of the magnetic moment of the magnet and the horizontal intensity while the oscillations give the product of the same two quantities Then from the time of one oscillation of the magnet and the angle through which the auxiliary magnet has been deflected combined with a number of constant factors, both the horizontal intensity and the magnetic moment of the magnet may be computed

Under certain conditions it is inconvenient or impossible to use the above method, as in the vicinity of the magnetic pole, where the horizontal intensity becomes very small, or on shipboard, where accurate oscillation observations are impossible on account of the motion of the ship In such cases use may be made of the method devised by Dr E Lloyd to determine the total intensity by means of a dip circle The method involves two operations, during both of which the dip circle is placed so that the suspended needle swings in the plane of the magnetic meridian First, the measure of the angle of inclination with a needle having a weight in the south end (in north magnetic latitudes) second, the measure of the angle through which a second needle is deflected by the loaded needle, when the latter is placed at right angles to it in the place provided for the purpose between the reading microscopes In the first case the earth's magnetism acting on the loaded (intensity) needle is opposed to the force of gravity acting on the weight In the second

case the force exerted by the intensity needle on the suspended needle is opposed to the earth's magnetism

The dip is usually measured in the field by means of a dip circle, shown in Figure 12, in which a magnetized needle is supported so as to be free to rotate about a horizontal axis A steel axle through the center of gravity of the needle terminates in finely ground pivots which rest on agate knife-edges The angle of dip is measured on a graduated circle concentric with the axle of the needle In order to measure the angle of dip directly the needle must swing in the plane of the magnetic meridian

Another instrument, called an earth inductor, which has been in use at fixed observatories for measuring the dip for many years, has recently been adapted for use in the field This instrument (fig 13) has a coil of copper wire wound on a cylindrical core An axis in prolongation of a central diameter of the core rests in bearings in a ring, in such a way that the core may be rotated by means of a piece of flexible shafting The ring has an axis at right angles to the axis of the coil, which is supported in a horizontal position on bearings in uprights attached to the alidade Attached to the ring is a graduated vertical circle, at right angles to the axis of the ring, by means of which the inclination of the axis of the coil may be measured The operation of the earth inductor is based on the fact that when a coil of wire is rotated in a magnetic field, a current of electricity is induced in the wire unless the axis of the coil is parallel to the lines of force of the field The operation of the instrument consists in placing the axis of the coil in the plane of the magnetic meridian and then changing the inclination of the axis of the coil until a position is found where no current is induced when the coil is rotated The angle of inclination of the coil as measured on the vertical circle is the angle of dip The presence or absence of a current is indicated by a galvanometer connected with the coil by suitable wiring, brushes, and a commutator

Special instruments have been devised for observations at sea On account of the instability of the ship as an observing platform the instruments must be mounted in gimbals so that they will remain approximately level in spite of the motion of the ship A magnetometer with fiber suspension can not be used A dip circle with needle supported in agate cups is used in place of one with agate knife edges for supports and the method of rotating the coil of the earth inductor has been modified The standard compass is used for declination observations and an attachment has been devised so that a deflector can be placed above the compass for determining the horizontal intensity

For more detailed information regarding instruments and methods of observing the reader is referred to Directions for Magnetic Measurements, Serial No 166 of the publications of the United States Coast and Geodetic Survey

MAGNETIC CHARTS

Practically all of the results of these various magnetic surveys have been published in one form or another by the organization doing the work The details are usually given in tabular form, but it is more convenient for many purposes to have a graphical

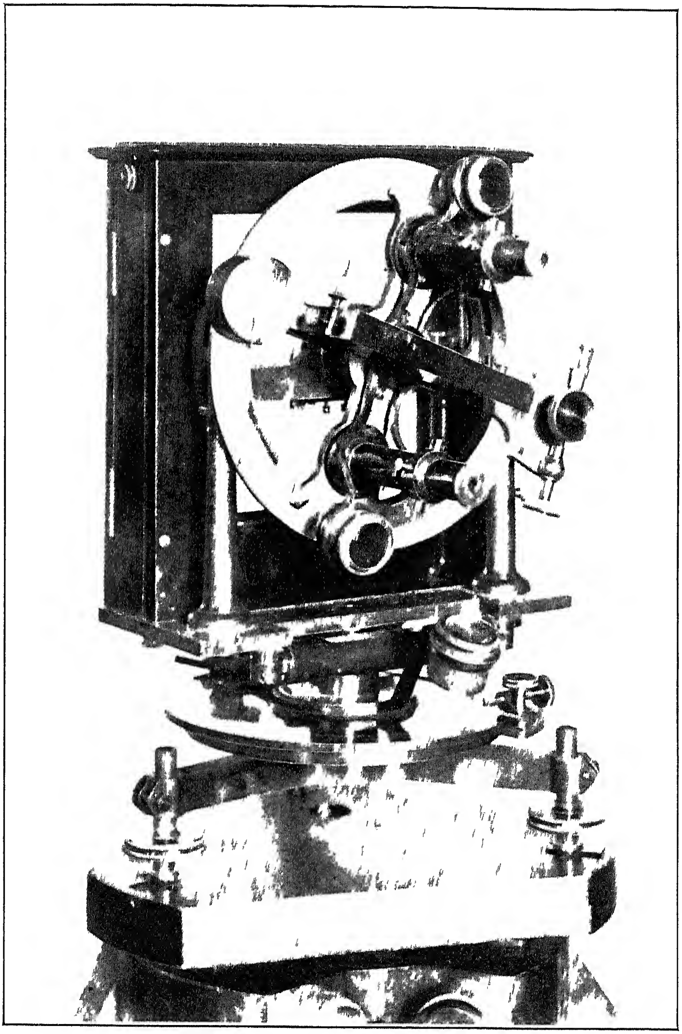

Fig. 12 —DIP CIRCLE

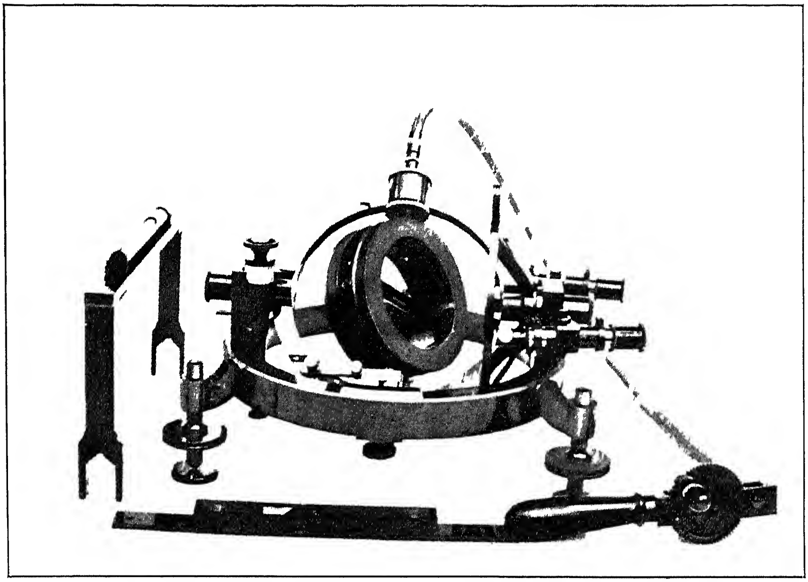

Fig 13 —EARTH INDUCTOR

representation of the general features and this is obtained by means of isomagnetic charts, that is, maps on which lines are drawn through the places having the same magnetic declination, the same dip, or the same horizontal intensity The chart showing the lines of equal magnetic declination is called an isogonic chart and this is the one for which there is most demand

For a limited area or where only scattering results are available it is possible to derive an empirical formula expressing the declination (or other element) in terms of the latitude and longitude, representing a uniform distribution over the area in question With increase in the number of stations it is at once seen that uniformity of distribution is exceptional and that the presence of local disturbances is the rule A more satisfactory representation of the ob-

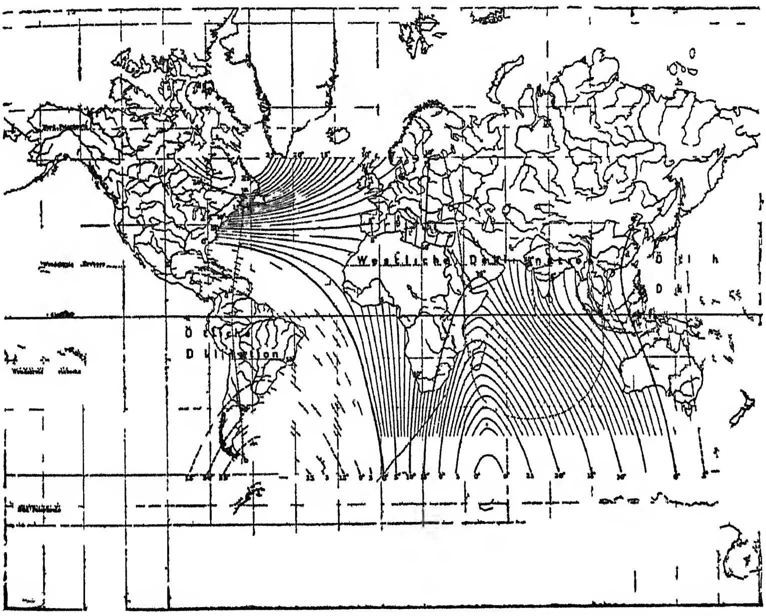

FIG 11 Lines of equal magnetic declination for 1700

served facts can then be secured by plotting the reduced values on a map and drawing the isomagnetic lines to conform to the plotted values In some regions it is impossible to represent the large local disturbances by continuous lines, but a disturbed area of limited extent may be represented by a small closed curve and isolated abnormal values can be given on the chart

In the case of declination it is usual to draw the isogonic lines differing by 1° In general, however, there are very few reduced values which are exactly the amount selected for a particular line—for example, there are very few stations at which the reduced declination is exactly 6° E —so that the location of a line must depend largely upon interpolation between values a little larger and a little smaller than the selected amount

The earliest magnetic charts are probably two constructed by Edmund Halley at the beginning of the eighteenth century One published in 1701 gave the lines of equal magnetic variation (declina

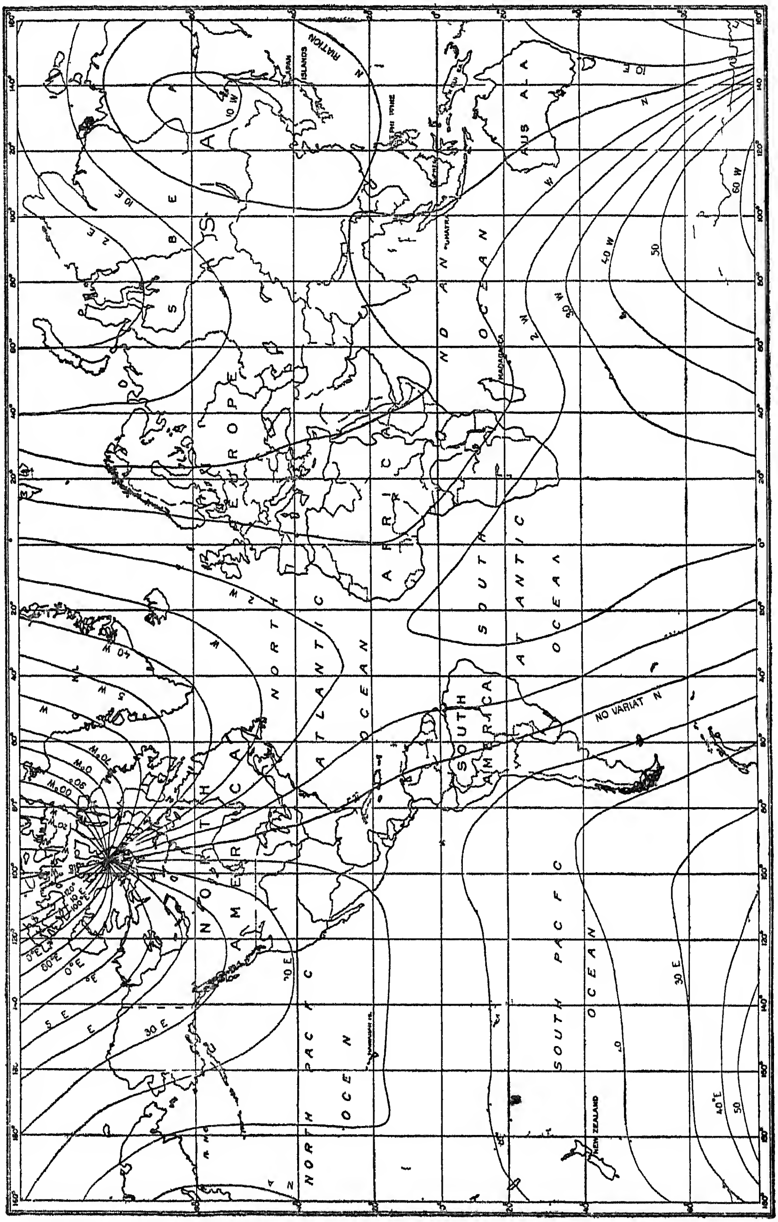

FIG 15 —Lines of equal magnetic declination for 1925 (From U S H O Chart 2406)

tion) over the Atlantic Ocean, based upon Halley's observations made between 1698 and 1701 on the ship *Paramour Pink*, at the expense of the British Government. The other (fig. 14), probably

published a year later, gave the lines of equal variation over the Indian Ocean and the extreme western part of the Pacific as well as over the Atlantic

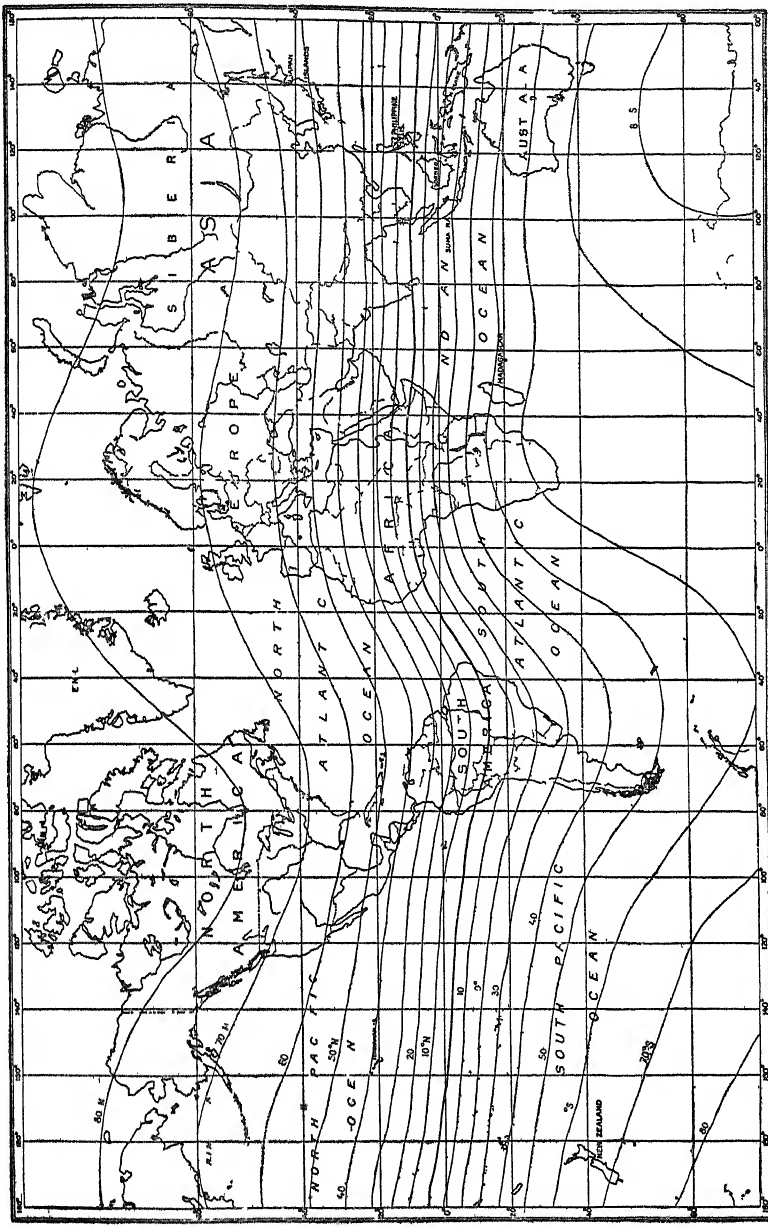

FIG 16—Lines of equal magnetic inclination for 1925 (From U S H O Chart 1700)

Such charts are indispensible for the navigator, and the hydro graphic offices of the leading maritime nations issue at regular intervals magnetic charts showing the lines of equal magnetic decli

nation, equal dip and equal horizontal intensity primarily for the ocean areas. Figures 15 and 16 showing the lines of equal declination and equal dip for 1925 are from charts issued by the United States Hydrographic Office. The points where observations have been made at sea are still far apart as a rule and only a general idea of the distribution is presented by the smooth curves.

Maps have been prepared showing the lines of equal magnetic declination in the polar regions but the number of observations is so limited that the lines are necessarily conjectural for a large part of the region within 20° of the North Pole and 30° of the South Pole except for the facts that all the lines pass through the geographic poles and that they all converge to the magnetic poles.

In Van Bemmelen's Die Abweichung der Magnet Nadel, published at Batavia, Java, in 1899, there is an extensive collection of early values of the magnetic declination and a series of isogonic charts for the years 1500, 1550, 1600, 1650, and 1700. The one for 1500 is shown in Figure 5. Although these early charts are necessarily only rough approximations because of the limited number of observations available, they nevertheless give a general idea of the change of the distribution of the magnetic declination over the earth's surface from century to century.

The United States Coast and Geodetic Survey has published magnetic charts of the United States at regular intervals since 1850. The last complete set was for 1915, in connection with Special Publication No. 44. An isogonic chart of the United States for 1920 was published with Special Publication No. 90, Magnetic Declination in the United States for January 1, 1920. One for 1925 is to be issued in 1926. This bureau has also published magnetic charts of Alaska, the West Indies, and the Philippines.

LOCAL DISTURBANCES

While the lines on the world magnetic charts appear as smooth curves, the isogonic charts of land areas which have been surveyed in detail, such as the 1920 chart of the United States, are characterized by crooked lines. Even then they do not fully represent the irregular distribution of declination over the country. In general it is found that when observations are made at additional stations in any region additional irregularities are developed. These are usually referred to as local disturbances, as contrasted with departures from regular distribution which are regional or continental in extent. In many cases values of declination differing by 1° are observed at places within 2 or 3 miles of each other, and occasionally much larger differences are observed, particularly in the vicinity of deposits of magnetic iron ore. In a small area near Juneau, Alaska, values of declination ranging from 175° W. to 170° E. were observed where about 31° 30′ E. would be expected, and at one spot the dip was 89° 59.4′, and the compass needle lost its directive property, so that the declination was indeterminate. Here the disturbing material was evidently quite near the surface and limited in extent, as the effect disappeared within a few miles of the point of maximum disturbance. At Port Snettisham, Alaska, there is an area of marked local disturbance which extends beyond the land nearly across the adjacent deep inlet. In the Province of Kursk, Russia, there is a

notable region of local disturbance extending for about 200 kilometers in a northwest southeast direction In Sweden the observed irregularities in the distribution of the earth's magnetism are used to develop the distribution of the magnetic iron ore which causes them

MAGNETIC POLES

The points on the earth's surface where the dipping needle stands vertical are usually referred to as the magnetic poles Excluding local magnetic poles, which occur in regions of extraordinary local disturbances with large masses of attracting material near the surface, there are two such points, one in the Northern Hemisphere and the other in the Southern Hemisphere, but not diametrically opposite to each other At these points all of the earth's magnetic force acts vertically downward, and there is no component in the horizontal plane to hold the compass needle in a definite direction, so that it can no longer be used as a guide The dip changes very slowly in the vicinity of the magnetic pole, consequently the condition of vertical dip needle applies to a region of considerable extent, when the accuracy attainable in dip measurements under field conditions is considered Outside of this region there will be a very weak force acting on the compass needle, and the direction of the pole will be indicated Only by a magnetic survey of a considerable area can the position of the magnetic poles be located with accuracy If there should be magnetic material in the region the problem would be rendered all the more difficult

In June, 1831, Capt James Clark Ross found that the dip was 89° 59′.5 at a place on Boothia Felix in latitude 70° 05′ 17″ N and longitude 96° 45′ 48″ W of Greenwich, and this was taken as the position of the magnetic north pole until recently Magnetic observations were made in that region by the expedition of Capt Roald Amundsen, of Norway, between 1903 and 1906, and although they did not actually observe a dip of 90° they were able to estimate the position of the magnetic pole from their observations, placing it about in latitude 71° N and longitude 96° W of Greenwich It should not be assumed, however, that the difference between this position and the one determined by Ross represents the change in the position of the pole in the interval between 1831 and 1904 Both of the determinations are only approximations, and while there is every reason to believe that the position of the magnetic poles is changing, the amount may have been more or less than indicated above

The south magnetic pole has not yet been reached From Ross's observations made in the Antarctic regions while in command of the ship *Erebus*, Duperrey deduced the position of 75° S and 138° E of Greenwich The nearest approach to the south magnetic pole was made by Ross on February 16, 1841, in latitude 76° 20′ S and longitude 165° 32′ E, the dip at this place being 88° 35′ The British expedition under Captain Scott on the *Discovery*, 1902–4, made a large number of observations at the winter quarters and on various sledging expeditions, as well as on the *Discovery* before she was frozen in A discussion of all of the declinations observation gave the probable position of the magnetic pole 72° 50′ S and 156° 20′ E

and of the dip observations the position 72° 52′ S and 156° 30′ E, a remarkably close agreement Douglas Mawson, of Shackleton's party, endeavored to reach the magnetic pole and actually observed a dip of 89° 48′ in January, 1909 By comparing this with the results of his previous observations he estimated the position of the pole as 72° 25′ S and 155° 16′ E Eric N Webb, of the Australian Antarctic expedition, made a large number of magnetic observations on the opposite side of the pole from Mawson, and on December 21, 1911, reached a point (70° 36′ S and 148° 12′ E), which he believed to be on the edge of the polar area His observations, however, indicate an irregular distribution of magnetism, and one is therefore inclined to place more reliance on the *Discovery* and Mawson results

It must not be forgotten that the points on the earth's surface termed "magnetic poles" are not to be thought of as comparable with the poles of a bar magnet The earth acts like a spherical magnet, and a bar magnet within the earth which would produce the magnetic effects observed at the surface would have its poles practically coincident Kraft and Biot found that the nearer to each other they assumed the poles of a fictitious bar magnet at the center of the earth, the closer the agreement between their computed results and the observed facts, so that the "equivalent magnetic poles" of a spherical magnet are practically the same distance from all points on the surface

The earth's magnetic poles are not even the points of maximum magnetic intensity In the Northern Hemisphere there are two regions of maximum magnetic intensity, the stronger one being in Canada in about latitude 52° and longitude 92° There are also two such regions in the Southern Hemisphere

MAGNETIC OBSERVATORIES

The fact that the earth's magnetism is constantly changing in direction and strength makes it necessary to supplement magnetic surveys, giving the distribution of the earth's magnetism at a particular time, by other observations to determine the changes which are taking place with lapse of time Fortunately it has been found that these time changes vary so slowly and regularly in going from place to place that for most practical purposes the determination of the changes at a limited number of well distributed stations by means of repeated observations gives sufficient data for finding the changes at intermediate stations Accordingly about 5 per cent of the magnetic stations in the United States are reoccupied about once in five years For many purposes, however, more detailed information regarding the time changes is needed, and this is secured by the operation of magnetic observatories

This need was clearly recognized from the time of Gauss and the number of observatories established then has been added to gradually until there are now about 50 in operation Nearly 50 per cent of them are in Europe but the rest are widely distributed—in Egypt, Mauritius, India, Java, China, Japan, Siberia, Philippines, Australia, New Zealand, Samoa, Hawaii, Argentina, Peru, Alaska, Canada, United States, Porto Rico The first observatory in the

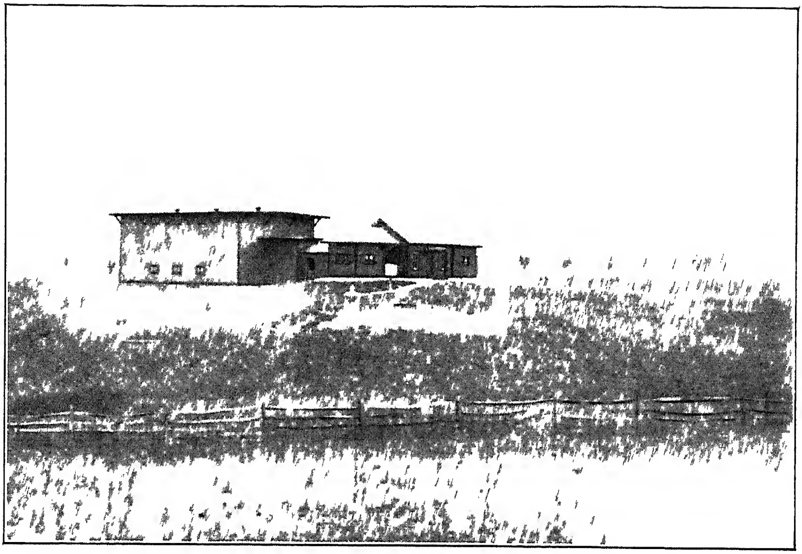

Fig 17 —COAST AND GEODETIC SURVEY MAGNETIC OBSERVATORY AT CHELTENHAM MD

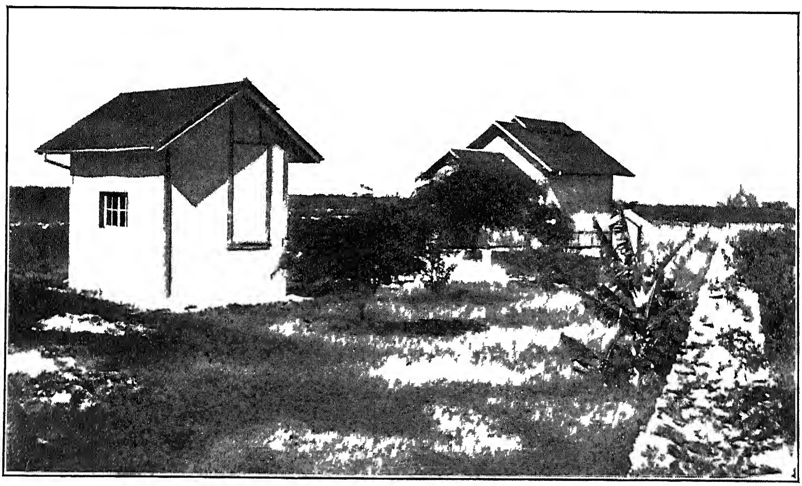

Fig 18 —COAST AND GEODETIC SURVEY MAGNETIC OBSERVATORY NEAR HONOLULU HAWAII

United States was at Girard College, Philadelphia, from 1841 to 1845 The observatory established at Toronto, Canada, in 1842, is still in operation, though the site had to be changed in 1899 because of electric railway disturbance The United States Coast and Geodetic Survey now maintains observatories at Cheltenham, Md, island of Porto Rico, Tucson, Ariz, Sitka, Alaska, and near Honolulu, Hawaii The observatory at Sitka is not far from the site of the one operated b ythe Russians from 1842 to 1867 The Department of Terrestrial Magnetism of the Carnegie Institution of Washington is operating observatories at Watheroo, Australia, and Huancayo, Peru

For the operation of a magnetic observatory there are required a variation building, in which the variation instruments are mounted, and an absolute building, in which the absolute observations are made In their construction great care is exercised to exclude all material that might possibly have a disturbing effect on the magnets and in their subsequent use the same care must be exercised The variation building is designed to reduce to a small limit the range of temperature inside, not more than a few tenths of a degree in the course of a day Those of the Coast and Geodetic Survey are all aboveground and built of wood and the desired insulation is secured by suitable air spaces and spaces filled with sawdust on all sides of the instrument room, varied at different stations according to the daily range of temperature outside the building

The variations in declination, horizontal intensity and vertical intensity are recorded photographically by means of three variometers and a recording apparatus Light from a lamp, reflected from a mirror attached to the suspended magnet of a variometer, traces an irregular line (curve) on a sheet of photographic paper (magnetogram) wrapped around a revolving drum of the recording apparatus The reflection from a fixed mirror traces a straight line (base line) on the magnetogram, and the variation in the distance between the curve and the base line is a measure of the variation in the direction of the suspended magnet produced by a change in the earth's magnetism

One variometer is mounted with its magnet in the magnetic meridian, and the direction of the magnet changes as the declination changes In another the magnet is suspended with its axis at right angles to the magnetic meridian, and a change in its direction corresponds to a change in the horizontal intensity In the third the magnet rotates about a horizontal axis, like a dip needle, but it is adjusted to lie approximately in the horizontal plane, so that a variation in its inclination to the horizon corresponds to a variation in the vertical intensity Each of the observatories of the Coast and Geodetic Survey is equipped with a magnetograph in which very small magnets are used, so that it is possible to have the variometers quite near to each other without appreciable interaction They are mounted in a row, magnetically east and west, and all three record on the same magnetogram The drum of the recording apparatus revolves once in 24 hours, a space of about 2 cm being passed over in an hour At hourly intervals a system of shutters is raised by

means of a cam attached to a gear wheel and after the lapse of a minute or two is allowed to drop back to its former position The shutters are so adjusted that when raised they prevent the light from the fixed mirrors from reaching the magnetogram and thus produce a short break in each base line

The variation instruments are controlled by absolute observations made at regular intervals with instruments similar to those used in field work and by suitable determinations of the instrumental constants They must be kept very sensitive so that they will record small changes as well as large ones and an observatory must therefore be well removed from all sources of artificial disturbance, particularly electric railways There have been many cases where it became necessary to move an observatory to a new site because of the construction of electric railways in the vicinity and an electric railway running out from the District of Columbia has an appreciable effect on the instruments at the Cheltenham observatory even at a distance of more than 12 miles

For the same reason any one entering the variation building must be careful first to divest himself of all articles of iron or steel, such as knives and keys The sole of a shoe may contain a piece of steel sufficient to produce an appreciable effect on the sensitive magnets of the variometers

Before photography had been developed to the point where it could be used to secure a continuous record of the movements of the magnets of the variometers, telescopes and scales were provided and eye readings were taken at regular intervals, usually once an hour, throughout the day

SECULAR CHANGE

Gellibrand's discovery that the declination at a place does not remain constant was later found to be true of the dip and intensity With lapse of time it was seen that the change does not go on indefinitely in one direction, eventually a turning point is reached At London, for example, the declination was nearly 11° E in 1580 The north end of the needle then began to move to the westward and in 1810 had reached a westerly extreme of over 24° W Since then the motion has been toward the east and the declination is now (1925) only about 13° W Similar changes are shown by the results of observations at Paris and Rome In the United States our observations do not go back so far nor do they show so great a range, however, at Boston, Mass, the declination decreased from over 11° W in 1670 to less than 7° W in 1785 and since then has been increasing until it is now over 14° W, and this is typical of the northeastern part of the country The changes of declination at a number of typical stations are shown in the following table and in Figure 19 The quantities in the table are not actual observed values but are derived by the method of least squares from results scattered irregularly over the period covered by the table The curves are graphical representations of the tabular quantities Further details of the secular change of the magnetic declination in the United States will be found in Special Publication No 90

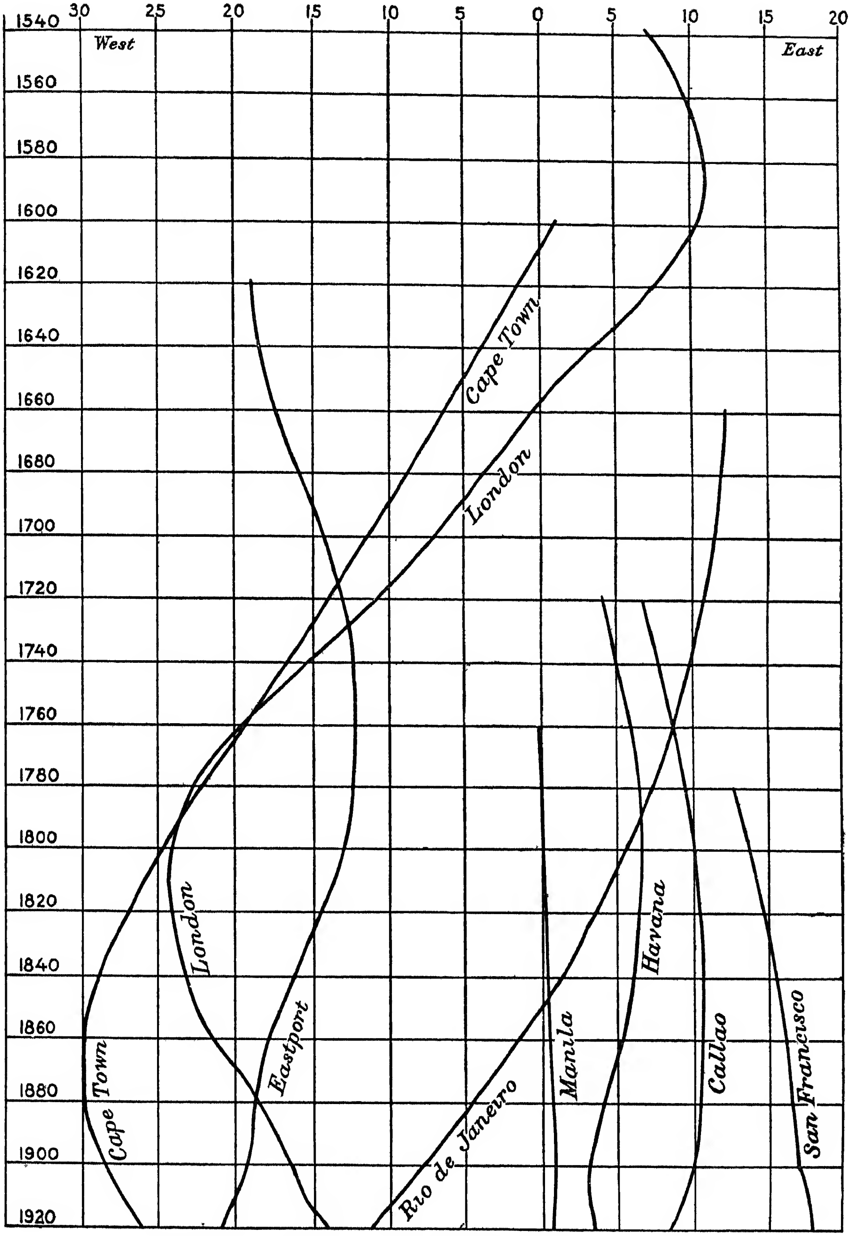

FIG 19 — Curves showing secular change of declination

Secular change in the magnetic declination at various places

Place	London England	Eastport Me	Habana Cuba	San Francisco Calif	Manila P I	Callao Peru	Rio de Janeiro Brazil	Cape Town South Africa
Latitude	51 28 N	44 55 N	23 07 N	37 48 N	14 36 N	12 04 S	22 54 S	33 56 S
Longitude	0 19 W	67 00 W	82 22 W	122 27 W	120 58 E	77 08 W	43 10 W	18 29 E
1540	7 2 E							
1560	9 6 E							
1580	10 9 E							
1600	10 1 E							1 0 E
1620	7 3 E	19 0 W						1 5 W
1640	3 3 E	18 5 W						4 0 W
1660	0 6 W	17 5 W					12 1 E	6 4 W
1680	3 9 W	16 0 W					11 8 E	8 9 W
1700	7 1 W	14.5 W					11 3 E	11 5 W
1720	11 0 W	13 1 W	4 0 E			6 7 E	10 6 E	14 0 W
1740	15 3 W	12 4 W	5 0 E			7 7 E	9 7 E	16 8 W
1760	19 6 W	12 2 W	5 8 E		0 1 W	8 6 E	8 5 E	19 4 W
1780	22 7 W	12 4 W	6 3 E	12 6 E	0 0	9 4 E	7 1 E	22 2 W
1800	24 1 W	13 2 W	6 5 E	13 6 E	0 1 E	10 0 E	5 5 E	25 0 W
1820	24 1 W	14.7 W	6 3 E	14.6 E	0 2 E	10 4 E	3 5 E	27 1 W
1840	23 2 W	16 3 W	6 0 E	15 4 E	0 3 E	10 6 E	1 2 E	29 0 W
1860	21 5 W	18 0 W	5 2 E	16 1 E	0 5 E	10 5 E	1 5 W	30 0 W
1880	18.7 W	18 8 W	4.0 E	16 5 E	0 7 E	10 3 E	4 4 W	29 8 W
1900	16 5 W	19 3 W	3 1 E	16 9 E	0 9 E	9 9 E	7 7 W	28 6 W
1910	15 7 W	20 0 W	3 0 E	17 6 E	0 8 E	9 2 E	9 5 W	27 5 W
1920	14 1 W	20 8 W	3 4 E	17 9 E	0 7 E	8 5 E	11 2 W	26 1 W

The importance of this change to the land surveyor may be realized when it is considered that a line 1,000 feet long run due north by compass in Boston in 1925 would have its north end 125 feet farther west than a line from the same starting point run due north by compass in 1785

From an inspection of the tabular quantities it will be seen that the rate of change is not uniform At the time of a maximum or minimum there is practically no change for several years Then the annual change gradually increases to a maximum and then decreases to zero at the next turning point Even for a decade the rate of change is not uniform, as will be seen from an examination of the following table, giving the annual values of declination at a number of magnetic observatories

Change of declination at observatories

Year	Greenwich England	Vieques P R	Cheltenham Md	Toronto Canada	Tucson Ariz	Sitka Alaska	Honolulu Hawaii
1905	16 09 9 W	1 38 3 W	5 17 8 W	5 42 2 W		29 59 1 E	9 21 7 E
1906	16 03 6 W	1 45 9 W	5 21 5 W	5 44 8 W		30 03 0 E	9 23 0 E
1907	15 59 8 W	1 53 7 W	5 26 0 W	5 50 6 W		30 07 1 E	9 24.3 E
1908	15 53 5 W	2 02 5 W	5 31 1 W	5 54.0 W		30 10 7 E	9 25 7 E
1909	15 47 6 W	2 11 7 W	5 36 4 W	5 59 4 W		30 13 1 E	9 27 3 E
1910	15 41 2 W	2 20 6 W	5 41 4 W	6 03 9 W	13 25 8 E	30 16 4 E	9 29 7 E
1911	15 33 0 W	2 29 9 W	5 45 6 W	6 09 0 W	13 29 7 E	30 19 1 E	9 32 2 E
1912	15 24 3 W	2 39 0 W	5 50 0 W	6 13 7 W	13 33 5 E	30 20 9 E	9 34 8 E
1913	15 15 2 W	2 49 6 W	5 54 6 W	6 18 4 W	13 37 0 E	30 22 0 E	9 37 3 E
1914	15 06 3 W	3 00 4 W	5 59 8 W	6 23 8 W	13 39 9 E	30 22 9 E	9 39 6 E
1915	14 56 5 W	3 10 1 W	6 04 0 W	6 28 5 W	13 42 5 E	30 23 2 E	9 41 6 E
1916	14 46 9 W	3 19 2 W	6 07 7 W	6 33 4 W	13 44 4 E	30 23 9 E	9 43 9 E
1917	14 37 0 W	3 27 0 W	6 10 4 W	6 36 2 W	13 46 1 E	30 24 7 E	9 46 3 E
1918	14 27 2 W	3 34 0 W	6 12 4 W	6 38 3 W	13 47 1 E	30 24 9 E	9 48 6 E
1919	14 18 2 W	3 39 9 W	6 15 0 W	6 41 0 W	13 47 8 E	30 26 7 E	9 50 8 E
1920	14 08 6 W	3 46 1 W	6 18 5 W	6 45 4 W	13 48 0 E	30 28 2 E	9 53 2 E
1921	13 57 6 W	3 53 3 W	6 22 4 W	6 50 6 W	13 47 8 E	30 28 7 E	9 55 3 E
1922	13 46 7 W	4 00 9 W	6 27 7 W	6 56 2 W	13 47 6 E	30 29 2 E	9 57 1 E
1923	13 35 1 W	4 08 3 W	6 32 0 W	7 00 9 W	13 47 3 E	30 28 9 E	9 58 9 E
1924		4 15 5 W	6 35 8 W		13 46 4 E	30 28 7 E	10 00 2 E

The secular change of dip so far as it has been developed is of the same general character as for the magnetic declination From Norman's value of 71° 50′ in 1576 the dip at London increased to about 74° 30′ in 1700, and since then has been decreasing until it is now less than 67° The earliest determination of the dip in the United States was made by Capt Othniel Beal at Boston in 1722, 68° 22′ From that time it increased to over 74° in 1860, then decreased to 73° in 1905, and then began to increase again

There are no absolute intensity results prior to 1830 and not many before 1850, but the general indications are that there has been a decrease in the intensity of the earth's magnetism since that time In the United States the total intensity was apparently increasing from 1840 to 1860, but since then it has been decreasing It will be seen from the following tables that the rates of change of dip and intensity are also quite irregular

Change of dip at observatories

Year	Greenwich England	Vieques P R	Cheltenham Md	Toronto Canada	Tucson Ariz	Sitka Alaska	Honolulu Hawaii
1905	66 55 9	49 17 0	70 25 4	74 34 3		74 43 2	40 05 0
1906	66 55 3	49 22 1	70 26 9	74 35 0		74 41 0	40 02 8
1907	66 56 1	49 29 3	70 29 0	74 36 4		74 38 4	39 59 1
1908	66 56 3	49 36 3	70 30 5	74 36 9		74 36 5	39 55 3
1909	66 54 0	49 44 1	70 32 8	74 37 5		74 34 6	39 51 4
1910	66 52 6	49 52 0	70 35 4	74 38 5	59 19 6	74 32.2	39 47 2
1911	66 52 1	50 00 4	70 37 4	74 39 1	59 19 9	74 30 4	39 42 2
1912	66 51 8	50 09 0	70 39 1	74 39 8	59 20 3	74 28 8	39 38 4
1913	66 50 4	50 21 2	70 41 1	74 40 8	59 21 8	74 27 7	39 32 6
1914	66 51 2	50 33 9	70 44 0	74 41 8	59 23 1	74 26 6	39 30 4
1915	66 51 8	50 45 9	70 46 8	74 42 9	59 24.7	74 26 5	39 29 1
1916	66 52 8	50 55 5	70 49 6	74 43 5	59 26 1	74 25 6	39 28 5
1917	66 53 6	51 02 7	70 51 5	74 44 2	59 26 4	74 24 8	39 27 1
1918	66 54 2	51 10 9	70 53 0	74 44 8	59 26 5	74 23 8	39 26 7
1919	66 53 3	51 17 7	70 54.4	74 44.9	59 27 0	74 23 2	39 25 8
1920	66 53 6	51 22 7	70 55 4	74 44 6	59 27 6	74 22 1	39 25 1
1921	66 53 0	51 28 4	70 56 5	74 44 5	59 28 0	74 22 6	39 24 5
1922	66 52 3	51 33 1	70 57 6	74 44.6	59 29 0	74 22 4	39 24 4
1923	66 51 9	51 38 1	70 58 3	74 44 3	59 28 8	74 22 1	39 23 9
1924		51 42 2	70 59 2		59 29 4	74 22 0	39 24 5

Change of total intensity at observatories

Year	Greenwich England	Vieques P R	Cheltenham Md	Toronto Canada	Tucson Ariz	Sitka Alaska	Honolulu Hawaii
	γ	γ	γ	γ	γ	γ	γ
1905	47274	44795	59878	61730		58797	38168
1906	47256	44799	59832	61680		58727	38124
1907	47304	44806	59781	61662		58631	38073
1908	47298	44782	59710	61602		58576	38021
1909	47218	44755	59642	61473		58512	37957
1910	47240	44734	59596	61421	53669	58426	37910
1911	47217	44716	59512	61219	53606	58362	37837
1912	47205	44692	59407	61166	53539	58300	37783
1913	47125	44702	59253	61053	53469	58256	37704
1914	47126	44712	59127	60923	53388	58187	37645
1915	47103	44710	58982	60795	53295	58138	37581
1916	47100	44672	58891	60682	53218	58055	37525
1917	47082	44640	58782	60586	53145	57999	37473
1918	47064	44644	58693	60497	53072	57925	37431
1919	47015	44626	58595	60396	53001	57884	37378
1920	47022	44582	58498	60291	52957	57800	37341
1921	46991	44569	58401	60186	52899	57816	37306
1922	46952	44538	58305	60078	52855	57766	37267
1923	46964	44514	58198	59964	52760	57707	37233
1924		44479	58101		52682	57654	37204

At one time it seemed probable that the secular change of the earth's magnetism was periodic in character and that after observations had been made for a sufficient length of time (at least several centuries) it would be possible to predict in a general way future changes. With the accumulation of more data, however, the phenomenon is seen to be more irregular and complicated than was at first thought and the prospect of predicting what changes may be expected in the future on the basis of what has taken place in the past has become more remote.

MAGNETIC STORMS

The changes from year to year shown in the above tables are not large, and the changes from day to day are as a rule correspondingly small, when the average value for one day is compared with the average value for another. The magnetic observatory records show, however, that the earth's magnetism is constantly changing and that in the course of a few hours a change may occur of the same order of magnitude as the change from year to year. A change in one direc-

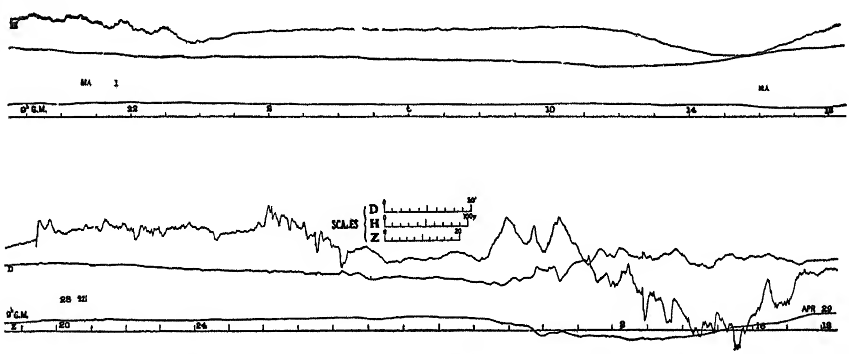

FIG. 20.—Magnetograms showing contrast between the records on quiet and disturbed days

tion is followed by a corresponding change in the opposite direction, so that the value at the end of a day is usually not much different from the value at the beginning.

The more marked and irregular of these periods of disturbance are called magnetic storms. They occur at irregular intervals; they usually accompany the appearance of large spots on the sun and the occurrence of auroral displays; at the time of storms of great severity there is usually difficulty in telegraphic communication; they usually occur at very nearly the same time all over the earth. This last is especially true of magnetic storms which begin abruptly, such as the one shown in Figure 20. In the United States the change in declination in the course of a magnetic storm may be anywhere from a quarter of a degree to a degree and the change in intensity may be as much as 1 per cent. The amplitude of the fluctuations is greater in high latitudes than in the equatorial regions. Thus at the time of the severe magnetic storm of November, 1882, the range of declination observed by Greely at Lady Franklin Bay, Grinnell Land, was over 20° as compared with 1⅓° at the magnetic observatory at Los Angeles, Calif.

Although most magnetic storms occur at practically the same time all over the earth, the detailed phases show marked differences at different places, both as to time and amplitude, indicating that a storm is partly cosmical and partly local in character Then too there are some magnetic disturbances which are recorded over only a limited portion of the earth's surface and do not occur simultaneously at all places within that area

DIURNAL VARIATION

In addition to these large irregular fluctuations there is a type of variation which repeats itself with considerable regularity day after day, called the diurnal variation Unlike the magnetic storms, which as a rule occur everywhere at practically the same time, the diurnal variation is in the main a local phenomenon, dependent upon the position of the sun with respect to the earth in its daily rotation about its axis and more particularly upon the position of the sun above the horizon The principal part of the change occurs during the daytime, during the night the fluctuations are small

The characteristic features of the diurnal variation are shown in Figures 21 to 23 It must be borne in mind that these curves are based on days selected because of their freedom from storms, and represent the average of a large number of days, so that minor irregularities are smoothed out and the average range (difference between extreme values) is somewhat reduced The time of occurrence of the maximum or minimum value may vary as much as two hours on different days An idea of the variation on an individual day may be obtained from Figure 20

Declination—North of the magnetic equator the diurnal variation of declination is characterized by an easterly motion of the north end of the needle in the morning, with an easterly extreme about 8 or 9 a m , then a westerly motion, with a westerly extreme about 1 or 2 p m , then an easterly motion for 4 or 5 hours From that time to the early morning there is little change The daily range is greater in summer than in winter and greater toward the magnetic pole than toward the Equator It should be noted, however, that for the winter group of months the daily range is about the same at Sitka as at Honolulu and less than at the intermediate stations, the time that the sun is above the horizon (only about 8 hours at Sitka as compared with 11 hours at Honolulu) apparently being one of the controlling factors In the Southern Hemisphere conditions are reversed, the westerly extreme occurs in the morning and the easterly extreme in the afternoon

The practical significance of the diurnal variation of declination may be seen from the following example In the United States in summer the north end of the compass needle points on the average about 10′ more to the west at 1 p m than it does at 8 a m Consequently a line 1,000 feet long run by compass at the time of the westerly extreme would have its terminal point 2 9 feet to the left of a line of the same length from the same starting point run at the time of the easterly extreme

Horizontal intensity and dip—In the case of horizontal intensity the diurnal variation has the same general characteristics in the northern and southern hemispheres, but they differ in different lati

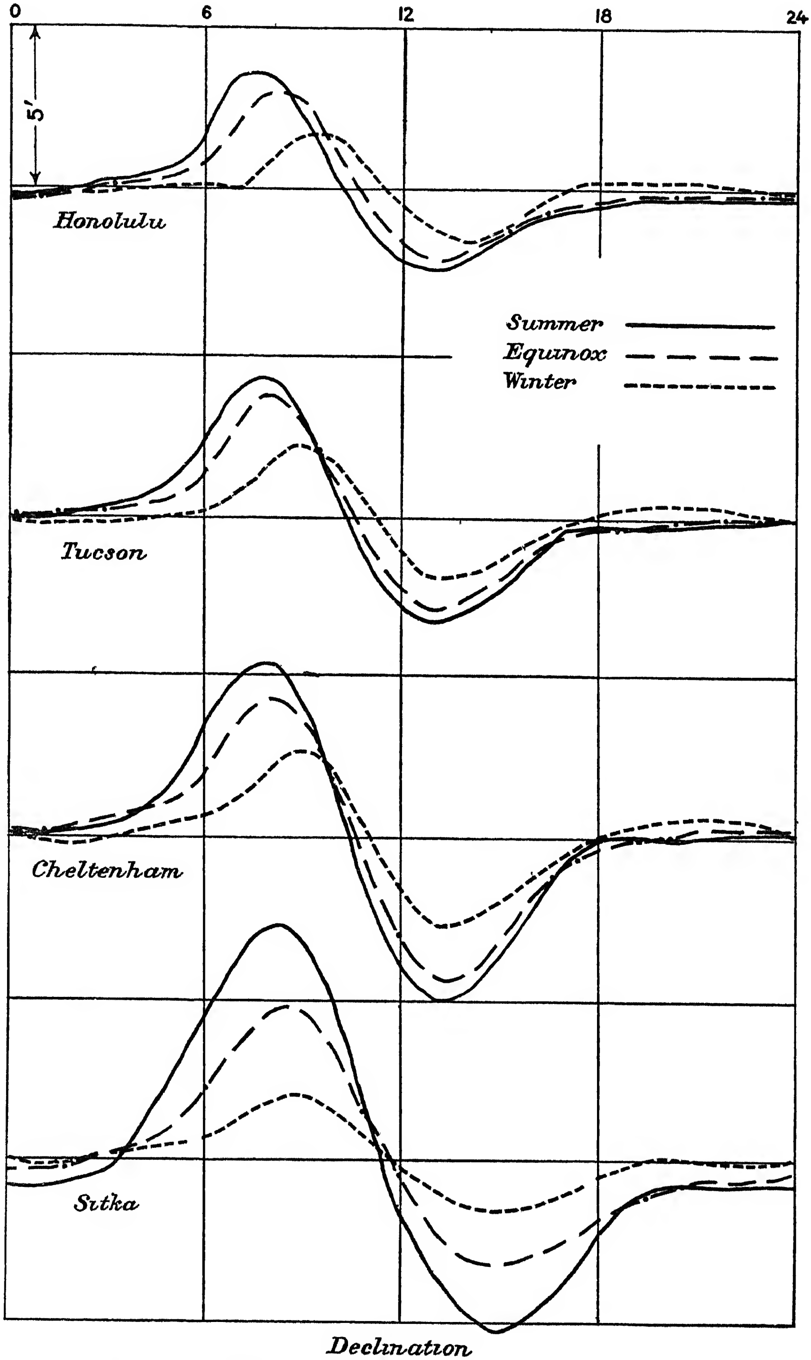

FIG 21—Curves showing diurnal variation of declination

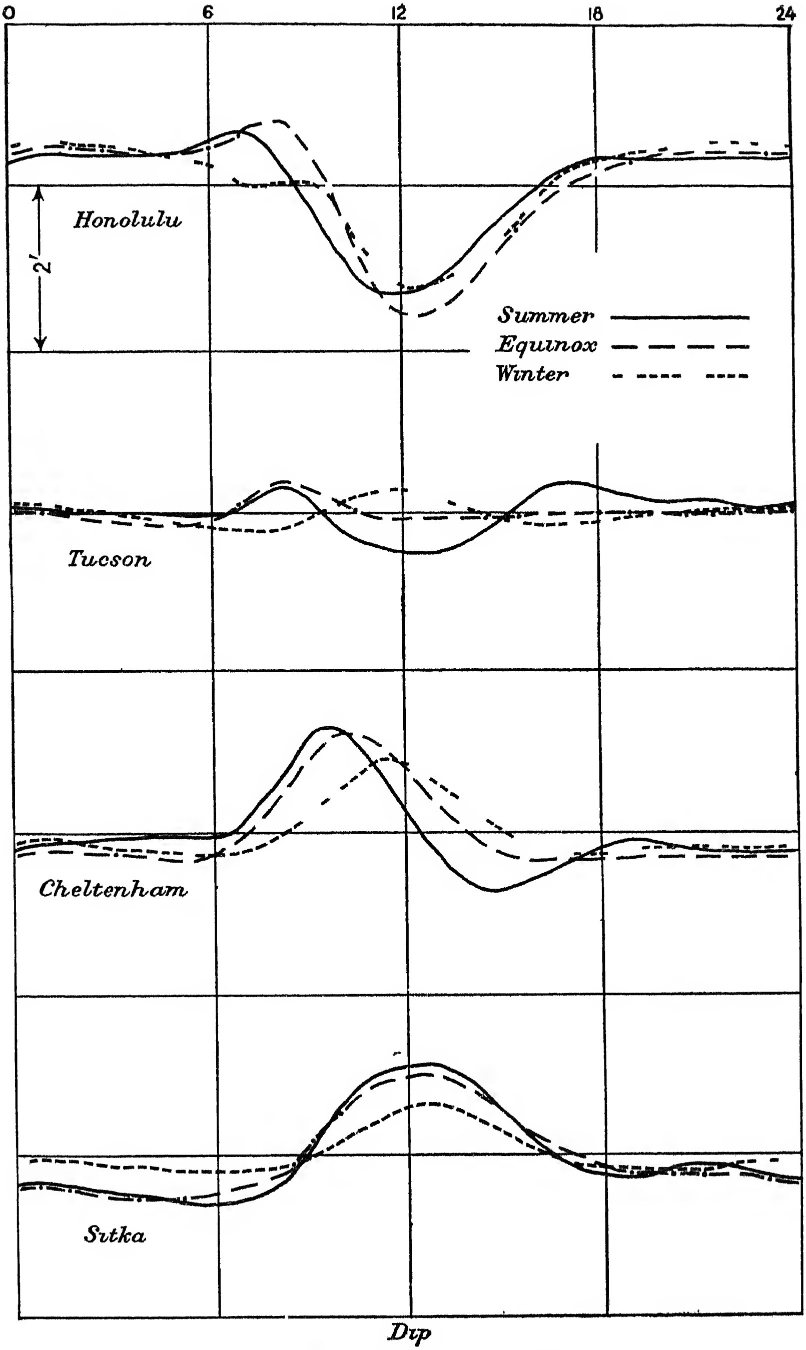

FIG 22 — Curves showing diurnal variation of dip

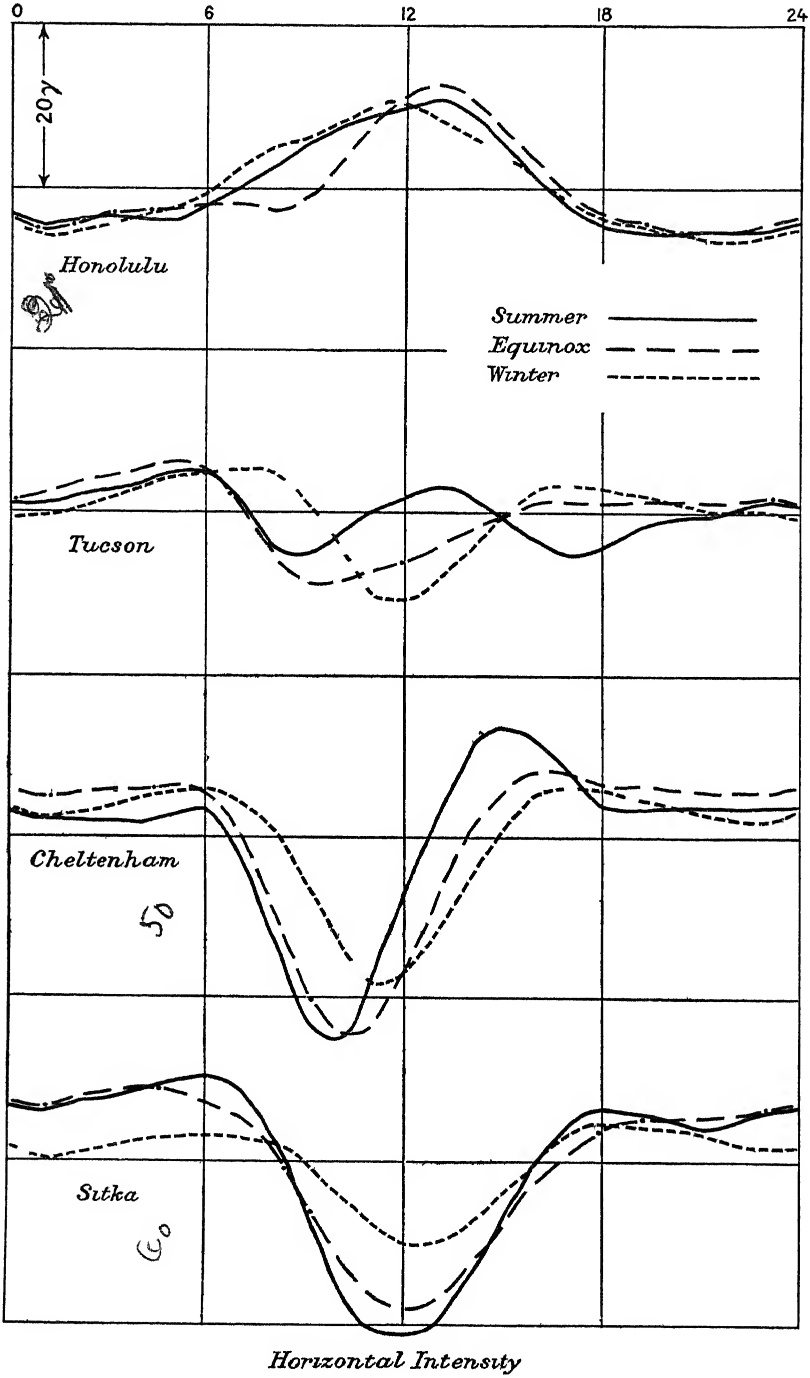

FIG 23—Curves showing diurnal variation of horizontal intensity

tudes At stations within 25° or 30° of the Equator the predominant feature is a pronounced maximum shortly before noon without a well defined minimum From about latitude 40° to the pole the predominant feature is a pronounced minimum shortly before noon Between, there is a transition belt, where the range is smaller and the variation less regular, sometimes with two maxima and two minima This difference is clearly shown by the curves for Sitka, Tucson, and Honolulu, in Figure 23 Tucson is in the transition belt, and the form of the curve is quite different for different times of the year

The diurnal variation of dip is of the same general character as that of horizontal intensity, with a predominant maximum or minimum shortly before noon, except in the transition belt In the case of total intensity there is a predominant minimum about noon at Tucson as well as at Cheltenham and Sitka, while at Honolulu and Porto Rico the range is small and the phases are less pronounced and different for different times of the year

THEORY OF THE EARTH S MAGNETISM

Coincident with the accumulation of observational data regarding the earth's magnetism by means of magnetic surveys and the operation of magnetic observatories there has been a continuous attack on the fundamental problems of the phenomenon What it is, what caused it, what causes it to change Many of the leading physicists and mathematicians of the past century have joined in the attack One theory after another has been advanced only to be withdrawn when it was found to be inconsistent with some of the observed facts Some theories fitted well enough qualitatively, but were entirely inadequate when quantity was taken into account, while others which seemed plausible at one stage of our knowledge had to be discarded when the extent of our knowledge increased

Advances in other fields of science have been seized upon in the hope that they might furnish a clue to the mystery of the earth's magnetism Cathode rays, the electronic theory of matter, the constitution of the sun, and the probable condition of the interior of the earth are all being studied as to their possible bearing on the magnetic field of the earth

Gilbert's conception of the earth as a great magnet uniformly magnetized about its axis of rotation, and subsequent modifications, could not be reconciled with the acceptance of a very high temperature for the interior of the earth and the recognition of the demagnetizing effect of heat, taken in connection with the small amount of magnetic material found in the visible rocks At the same time the magnitude of the departures from a uniform magnetization indicated the presence of large masses of magnetic material not far from the surface Recent investigations in various fields have suggested the possibility that some of the properties of matter subjected to very great pressure may be materially different from those observed at ordinary pressures Susceptibility to magnetization may be one of those properties and the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, with the cooperation of the Geophysical Laboratory of the same institution, is arranging a

series of experiments designed to test the matter With an inner core of the earth composed almostly entirely of iron and nickel, as suggested by some geophysicists, and the possibility that it may be susceptible of magnetization in spite of the high temperature, because of the enormous pressure, some magneticians are inclined to give further consideration to the idea of the earth as a great magnet

When it seemed clear that the conception of the earth as a permanent magnet could not be sustained, the idea was advanced that the earth's magnetic field might be due to electric currents flowing about the earth, either below the surface or in the atmosphere—the earth an electromagnet The mathematical analysis of the earth's magnetic field, according to the method devised by Gauss and extended by Neumayer and Peterson (1891) and Schmidt (1896), indicated that a small portion of the earth's magnetism, perhaps one fortieth, could be referred to forces outside the earth, another small portion to vertical electric currents, but by far the larger part to a system of forces within the earth A new analysis made by Bauer in 1922, using improved data based on modern observations, gave approximately the same result He reached the conclusion that for a satisfactory representation of the observed data it is necessary to recognize the existence of an internal magnetic system constituting about 94 per cent of the total field, with an external system and a non potential system each amounting to about 3 per cent

A comparison of his results with those previously obtained for the epochs 1842 and 1885 indicated that the intensity of magnetization of the earth had been decreasing during the 80 years at an average annual rate of one part in 1,500, a rate of loss which it is hard to reconcile with the age of the earth and the present intensity of magnetization unless we suppose that there have also been periods of increasing intensity

The idea of the earth as an electromagnet naturally suggested the possibility that its magnetism may be caused by its rotation This possibility has been the subject of much study, particularly by S J Barnett, who has shown that a piece of iron may be magnetized by rotation, though the observed effect was much too small to account for the earth's magnetism In 1900 Sutherland suggested as a possible cause of the earth's magnetism the rotation of an electrostatic field within the earth—a positively charged core and a negatively charged crust, or vice versa The development of the electronic theory of matter, with the atom consisting of a positively charged nucleus surrounded by negatively charged electrons, led Sutherland to suggest that if for some unknown reason, connected perhaps with gravitation, the negative charge of the atom was farther from the center of the earth than the positive charge by only 4×10^{-9} cm it would account for a magnetic field comparable with that of the earth When the electronic theory had been more fully developed and Sutherland's hypothesis submitted to further test it was found to be untenable either qualitatively or quantitatively

Failing to find a satisfactory explanation of the earth's magnetism on the basis of the known properties of matter and the accepted laws of electrodynamics, Sutherland, Bauer, and Swann have suggested that we may have to look for some slight but fundamental modification of those accepted laws, possibly as regards the mutual attraction

and repulsion of moving positive and negative electrons, similar to a suggestion by Lorenz regarding the cause of gravitation Indeed there seems to be growing a belief that gravitation and terrestrial magnetism are very closely allied and probably to be traced to a common origin

In view of the difficulties in the way of a direct solution of the problem of the cause of the earth's magnetism, magneticians have turned their attention to a study of its variations and their correlation with associated phenomena, such as atmospheric electricity, earth currents, auroras, sun spots and solar radiation, in the hope that the cause of the variations might be discovered, and that in that way light would be thrown on the main problem In particular, magnetic storms, those irregular disturbances of large amplitude and comparatively short duration, have been the subject of much study

It frequently happens that the occurrence of magnetic storms and auroras coincides with the presence of large spots on the sun, and this naturally has led to attempts to trace a causal relationship It was soon seen that a direct magnetic effect by the sun was out of the question, because of the great distance With the development of the idea that the earth's magnetism may be caused by currents of electricity, different forms of electric discharge emanating from the sun were successively put forth as the cause of the observed terrestrial phenomena, the theories advanced keeping pace with the development of our knowledge of electrical discharges in a vacuum

The correlation of magnetic storms with sun spots, although very satisfactory when based on yearly averages, leaves much to be desired when individual cases are considered Thus severe magnetic storms sometimes occur when no large sun spots are visible, and on the other hand the appearance of a sun spot is not always accompanied by a magnetic storm Large magnetic storms frequently follow each other at an interval approximating the time of revolution of the sun and such recurrence has been traced for several rotation periods, not every recurrence being accompanied by a visible sun spot, however To meet these conditions Maunder advanced the hypothesis that the solar activity which gives rise to magnetic disturbances on the earth does not act equally in all directions but along narrow well defined streams, not necessarily truly radial, that these streams arise from active areas of limited extent, that these active areas are not only the source of our magnetic disturbances but are also the seats of the formation of sun spots, that these areas can be active both before a spot has formed and after it has disappeared

Birkeland, Arrhenius, and Nordmann agreed in considering the aurora as a luminescence produced by the absorption of cathode rays in the upper atmosphere and attracted toward the earth's magnetic poles Birkeland, who devoted many years to the study of auroras, advanced the theory that cathode rays from the sun set up electric currents in the atmosphere which in turn give rise to secondary cathode rays He supported his theory by the production of artificial auroras in the laboratory, about a magnetized steel ball in a tube of rarefied air exposed to cathode rays

If magnetic disturbances on the earth are to be ascribed to streams of electrified particles shot out from the sun, we should expect to find a disturbance occurring first at the part of the earth

first entering the stream and later at other places as they in turn entered the stream, as a result of the combined motion of the earth in its orbit and the sun about its axis From the time of the earliest comparison of photographic records from widely separate observatories, it was recognized that the more severe magnetic disturbances occur at practically the same time all over the earth, and further comparative study of abrupt beginnings and sharp turning points indicated strict simultaneity, the departures therefrom being ascribed to errors inherent in the time measurements, so that more accurate determination of the time of occurrence of such salient features was suggested as a method of determining differences of longitude In fact, Van Bemmelen from the mean of 53 abrupt beginnings computed the difference of longitude between Batavia, Java, and Greenwich, and obtained a value differing by only 9 seconds from the one derived in the usual way

A later discussion of another series of abrupt beginning magnetic storms by Bauer and Faris indicated that the time of occurrence was not strictly simultaneous all over the earth but that the storm progressed, sometimes from west to east and sometimes from east to west, with a velocity which would carry it completely around the earth in three or four minutes Data from another series of storms, where an especial effort was made to secure more accurate time determinations and more homogeneous selection of starting points, indicate that if a storm occurs at one place before it does at another the speed of propagation is more rapid than that given above, as the observed differences of time at different observatories were not much in excess of the errors of measurement Rodes also made a study of a number of abrupt beginning storms and found some indication that such a storm may occur first at the "front meridian," that portion of the earth, that is, which would be the first to run into a stream of electrified particles coming from the sun These investigations are being continued in the hope that they will throw additional light on the connection between solar activity and magnetic storms on the earth

The researches of Hale at the Mount Wilson solar observatory, indicating that the sun has a magnetic field similar to that of the earth and that sun spots occurring in pairs are of opposite polarity, have further stimulated the efforts to trace a connection between solar and terrestrial magnetism One of the latest results of these researches is the establishment of the fact that while for a period of 11 years beginning with sun spot minimum the preceding spot shows negative polarity in the Northern Hemisphere and positive polarity in the Southern Hemisphere, in the succeeding 11 year period the conditions are reversed

When we attempt to account for the diurnal variation of the earth's magnetism a different problem is presented Here we have a phenomenon of local mean time, as contrasted with magnetic storms, which, as we have seen, occur everywhere at practically the same absolute time Broadly speaking the diurnal variation is a function of the position of the sun above the horizon, distinctly a local phenomenon The extremes and the principal portion of the variation occur during the daytime During the night hours there is comparatively little departure from the mean for the day In

view of this fact, it occurred to Bauer that the interposition of the moon between the sun and the earth at the time of a solar eclipse might have an appreciable effect on the earth's magnetism, tending to produce night conditions Accordingly he arranged for special observations by observers of the Coast and Geodetic Survey at the time of the solar eclipse of May 28, 1900, at stations along the belt of totality from Alabama to Maryland The results indicated a small but definite disturbance associated with the passage of the moon's shadow across the place of observation, and of the character to be expected Similar observations have been made at all accessible solar eclipses since that time, principally on the initiative of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, but with the cooperation of other observers in the countries crossed by or contiguous to the belt of totality These have tended to confirm the results of the first series, though the effect indicated is so small that it can not be definitely recognized when ordinary magnetic disturbances are in progress

These and other investigations point clearly to the sun as the cause of the diurnal variation of the earth's magnetism Various theories have been advanced as to how the effect is produced Perhaps the most plausible is that some electrical emanation from the sun produces a variation in the ionization of the upper atmosphere, with a resulting change in its conductivity and in the electric currents flowing about the earth

The cause of the secular change of the earth's magnetism has been the subject of much study Absolute determinations of the intensity of the earth's magnetic field did not begin until 1830 and it is only within the past few years that reliable observations covering the greater part of the world have been available, so that definite conclusions can not be expected At first it was thought that there might be a systematic change in the direction of the magnetic axis of the earth, causing corresponding changes in declination and dip, but it was soon found that the observed changes at different stations could not be brought into harmony with such a theory

Bauer has made a mathematical analysis of the secular change of the earth's field as a whole, based on a comparison of observed conditions in 1842 and 1922, and concluded that the system of forces involved is partly within the earth and partly outside and that the strength of the field is changing as well as its direction

Variation of solar activity has been suggested as one cause of the secular change of the earth's magnetism The periodic change in the number of sunspots, which is undoubtedly a symptom of varying solar activity, is paralleled by an 11 year period in the secular change, and Bauer has attempted to trace a relationship between changes in the earth's magnetism and the changes of solar activity indicated by Abbott's observations of the amount of heat given off by the sun Abbott's observations have not yet been going on long enough, however, to draw any definite conclusions

It will be seen that the studies of these three types of changes in the earth's magnetism all point to the sun as the ultimate cause, with variable electric currents in the earth's atmosphere one of the connecting links, but no satisfactory theory to complete the con

nection has yet been developed Any theory of the earth's magnetism based on electric currents either within or without the earth must take account of the currents actually observed, and one of the features of the progress of the past 25 years has been the awakening of interest in the study of atmospheric electricity and earth currents Before long we may expect the increase of our knowledge of radio transmission to throw light on electrical conditions of the atmosphere at higher levels

In spite of the progress made in accounting for the changes of the earth's magnetism the fundamental problem still remains, but in a modified form Its scope has broadened tremendously so that any theory to explain the earth's magnetism must take into account the structure of the atom as well as the structure of the universe However, new weapons and new methods of attack have been developed, and the workers in other fields of science—astronomer, physicist, geologist, chemist—are now the allies of the magnetician Moreover, an accurate magnetic survey of practically all of the accessible land and water areas and the operation of additional magnetic observatories, better distributed, have provided for the first time the reliable observational data which must form the ultimate test of any theory The problem is recognized as world embracing, and continuation of the necessary international cooperation is assured by the establishment of the section of terrestrial magnetism and electricity of the International Geodetic and Geophysical Union While the need for accurate observational data has in part been met, it must not be forgotten that the earth's magnetism is constantly changing, and the period of years for which we have accurate knowledge is still extremely small as compared with the age of the solid earth It is of fundamental importance for the study of the phenomenon that a continuous record of the changes which are taking place be assured, both by the operation of well distributed magnetic observatories and by the reoccupation of secular change stations or repetition of magnetic surveys at suitable intervals both on land and at sea

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